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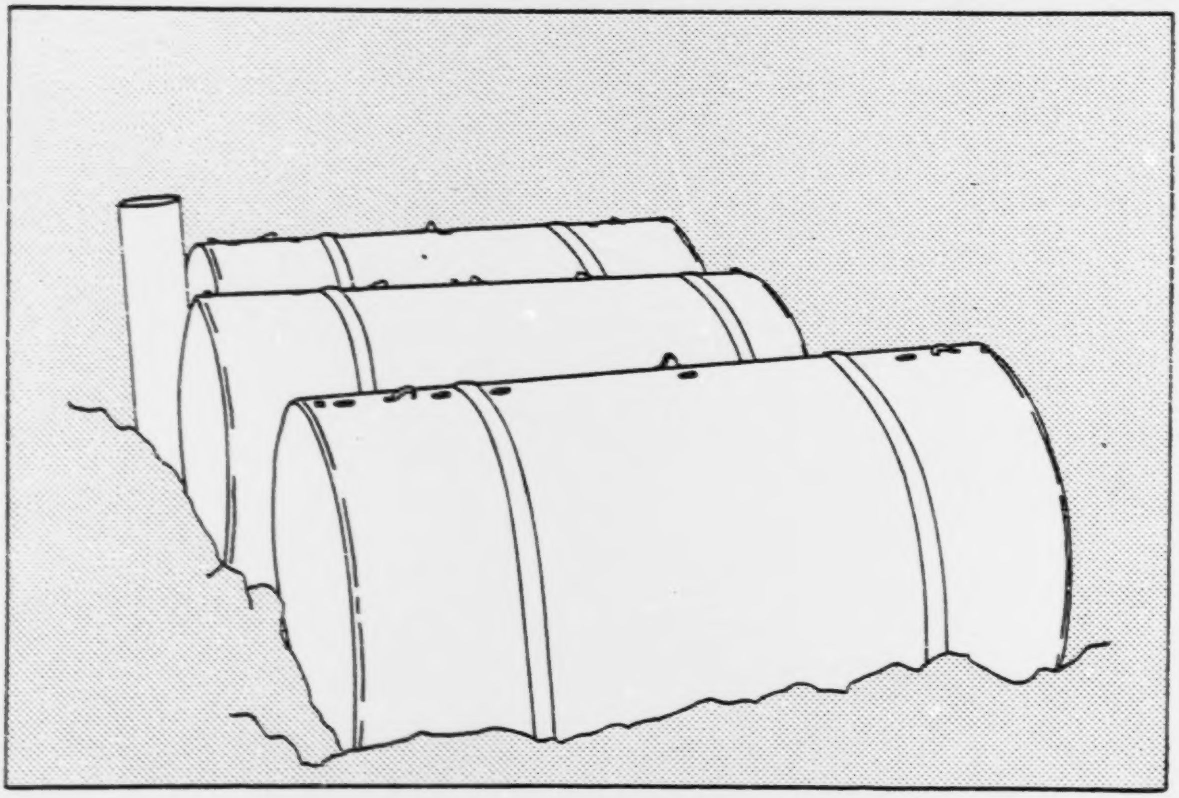

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DEVELOPMENT OF A TANK TEST METHOD FOR A NATIONAL SURVEY OF UNDERGROUND STORAGE TANKS

by

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For

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PREFACE

This revised draft final report was prepared for the U.S. Environmental Protection Agency under EPA Contract No. 68-02-3938, Work Assignment No. 25. The report describes an evaluation of methods for determining leaks in underground tanks used to store motor fuels and a pilot study conducted in preparation for a national survey of underground storage tanks. The work assignment was directed by Dr. Ken Wilcox under Dr. Clarence L. Haile, Deputy Program Manager. Technical support at MRI was provided by Dr. Jairus D. Flora, Ms. Marilyn Gabriel, Ms. Sharon Perkins, Mr. Brad Combs, and Mr. Ed Olson.

Two key MRI consultants contributed to the success of the program. Dr. Joseph W. Maresca, Jr., Vista Research, Inc. provided additional data analysis and evaluation methods. Mr. William Purpora, Protanic, Inc., provided guidance in field testing procedures and data evaluation.

Several U.S. Environmental Protection Agency personnel were instrumental in the success of the project. Mr. Michael R. Kalinoski and Mr. Tom Murray were Work Assignment Managers for EPA, and Dr. Joseph Breen, Project Officer for the program, provided key input to the project and were involved in many helpful discussions of the testing procedures and evaluation of the data. Additional input from the EPA was presented by Dr. Frederick W. Kutz, Mr. Martin Halper, Mr. Joseph Carra, and Mr. Robert Heath.

Excellent cooperation was received from those responsible for providing test facilities. In particular Mr. Andres Talts, Defense Environmental Leadership Project, and Major Patrick Fink, U.S. Air Force, were extremely helpful in obtaining cooperation at the various military facilities where testing was conducted. Mr. Glen Pugmire, Amoco, provided a site and fuel for the preliminary testing in Kansas City. Mr. Fred Sanders, Amoco, was most helpful in providing support on a daily basis during that time. Mr. Dave Carpenter, Texaco, also provided a site and fuel for the temperature study which was conducted in Kansas City.

Excellent cooperation was also received from the various test companies who participated in the program. Helpful comments and information were provided by Ms. Joyce Rizzo, Hunter Environmental Services, Inc. (Leak-Lokator), Mr. Tom Collins and Mr. Frank Senese, ARCO Petroleum Products Company (ARCO Tester), Mr. John Copus, O. H. Materials Company (Petro-Tite), Mr. William Burkhart, Smith and Denison (Varian Helium Leak Detector), Mr. John Nedbed, Fuel Recovery Environmental Services, Inc. (Certi-Tec), Mr. Jack Stillwagon, Heath Consultants (Petro-Tite), Mr. Eugene Collins, National Institute of Petroleum and Energy Research, and Dr. Jon Young of Ohio State University.

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16. ABSTRACT

Leaking underground storage tanks have become a matter of national concern. Materials leaking from underground tanks can pose a risk of groundwater contamination and, in the case of flammable materials, a risk of fire or explosion. The United States Congress, in recognition of this problem, mandated the Environmental Protection Agency to develop regulations for underground storage tanks containing motor fuels. As a part of the regulatory process, EPA was mandated to conduct a national survey of underground fuels storage tanks. The objectives of the project were to evaluate and select a suitable method for testing the tanks, quantify the performance of the recommended method, and develop a standard operating procedure for tank testing for the national survey. The initial phase of the project was a preliminary evaluation of existing tank test methods by literature review and field observation. Five candidate methods were evaluated using a single controlled underground tank. The three most promising of these were subjected to field evaluation at five geographically diverse installations. Based on these evaluations, a modified Petro-Tite test method was tentatively selected for the national survey. The modifications required taking more frequent readings, a longer test duration, and the use of sophisticated results analysis.

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17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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16. Abstract (Concluded)

Finally, the selected method was evaluated in a pilot study. Some additional method refinements resulted from the pilot study analysis. An operating procedure was developed for use of the recommended method on the national survey.

This report was prepared by Dr. Wilcox, Dr. Flora, Dr. Haile, Ms. Gabriel, and Dr. Maresca.

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EXECUTIVE SUMMARY

Leaking underground storage tanks have become a matter of national concern. Loss of materials stored in underground storage tanks poses a risk of contamination of ground water with an attendant potential risk to human health. In the event that the material is a flammable liquid such as motor fuels, leaks from underground storage tanks may pose an additional risk of fire or explosion.

The United States Congress recognized this problem and incorporated a new subtitle in the Hazardous and Solid Waste Amendments of 1984, signed by President Reagan on November 8, 1984. As part of the provisions of Subtitle I of the Resource Conservation and Recovery Act (RCRA), the U.S. Environmental Protection Agency (EPA) was mandated to develop regulations for underground storage tanks (USTs) to reduce the risk of leaks and the resultant risk to human life and property. As part of this regulatory process, EPA was mandated to conduct a national survey of underground storage tanks used to store motor fuel. The objectives of the national survey are:

1. To provide estimates of the total number of underground motor fuel storage tanks.

2. To provide estimates of the number of establishments with underground motor fuel storage tanks.

3. To provide estimates of the number of such tank systems that leak.

4. To collect information on the characteristics of tanks and tank establishments.

A part of the national survey was to include physical tightness testing for a national probability sampling of tanks. This project provided input by evaluating and recommending methods of tank testing for use in the national survey.

The objectives of this project were:

1. To select a method for physical testing of underground storage tanks used to store motor fuel to determine if they leaked.

2. To quantify the performance of the recommended method in terms of its precision, accuracy, and suitability for use in a national survey.

3. To define the standard operating procedure of the recommended method for use in the national survey, thus ensuring consistent data of high quality.

In order to achieve these objectives, several guidelines for judging methods of testing tanks were developed. These guidelines related to the performance of the method and to its suitability for use in the national survey. In developing these guidelines, the objectives of the national survey were explicitly considered. Methods were judged on their performance in measuring leaks from underground storage tanks. In addition, they were judged on their ability to identify and compensate for sources of interference from temperature changes, tank deformation, water table, etc. Because of the need for a large number of tests in a short time for the national survey, availability of equipment and trained personnel to do the testing was a factor, as was consideration of the impact and inconvenience to the owner/operator of the tank.

In achieving the objectives of this project, a five step approach was used. The first phase was a preliminary evaluation of existing methods. This included both a literature review and field observation of selected methods during use in testing tanks.

The second phase consisted of evaluative testing of five selected methods. The tests were carried out to measure performance in a controlled setting.

The third phase was field evaluation of three potential methods at five geographically scattered sites. Performance was checked under a variety of different environmental and operating conditions in the field.

The fourth phase, using the data resulting from the previous phases and comparing performance with the selection guidelines, recommended a method for use in the national survey. The recommendation was then discussed with EPA.

The fifth phase of the study was a pilot test of the recommended method designed to test its performance under the conditions proposed for the national survey. This phase checked the field operation for problems and difficulties. It also checked the advertised standard operating procedures for the method to ensure that they were practical and would provide a consistent set of high quality data on tank test results. Potential difficulties and suggested solutions resulting from the pilot study were used to adjust the standard operating procedures for use in the national survey.

The principal conclusions of the project are:

- After the evaluation of a number of test methods, it is clear that none of the standard test methods evaluated in the program can consistently and reliably achieve detection of the 0.05 gal/h leak rate specified by the NFPA 329, "Recommended Practices for Underground Leakage of Flammable and Combustible Liquids, 1983." This conclusion is based entirely on the data collected during the method selection phase of the program since supporting data which had been requested from the test companies to document their performance claims were not received.

- While some methods can provide reliable results under some specific conditions, there are many situations which commonly occur in the test environment (such as the presence of a water table) which can invalidate the test results. Unless the test crew takes specific steps to identify these conditions, the reported results may be either misleading or incorrect. Most test methodologies currently in use fail to take definitive steps to identify one or more of these problem areas. The test results obtained must therefore be suspect to the degree that these factors have not been recognized. The effects of not identifying these conditions can be substantial and, in general, cannot be evaluated from the test data after the test crew has left the test site.

- Of the methods evaluated during this program, the Petro-Tite method was selected as offering the most promising approaches to identifying potential problems and taking action to correct them. It has stated procedures to identify and correct for tank end deflection, temperature effects, water table, and vapor pockets. It was also judged to provide the most consistently reliable data overall. On the other hand, the precision of this test method was judged to be inadequate. The Petro-Tite method, which uses only four 15-min data points would have a probability of only 28% of detecting a 0.1 gal/h loss of product if the probability of false alarm is held fixed at 5% (two-sided). Better precision was required for the national survey.

- To improve the precision of the test results and our ability to identify potential interference problems, the Petro-Tite method was modified. The performance of this modified Petro-Tite method was then characterized as part of a pilot study. The method was modified by increasing the frequency method and applying specific statistical tests to the test data. Based on the performance of the modified method in the pilot study, the precision was improved so that an average probability of detecting a leak of 0.1 gal/h was estimated to be 95%. In other words, the modified Petro-Tite testing method combined with the statistical analysis of the test data has a 5% change of erroneously classifying a sound tank as unsound. On the average, it has a probability of 95% of detecting a product loss of 0.1 gal/h or larger.

This modified Petro-Tite method was recommended for use in the national survey.

I. INTRODUCTION

Leaking underground storage tanks have become a matter of national concern. Loss of materials stored in underground storage tanks poses a risk of contamination of ground water with an attendant potential risk to human health. In the event that the material is a flammable liquid such as motor fuels, leaks from underground storage tanks may pose an additional risk of fire or explosion.

The United States Congress recognized this problem and incorporated a new subtitle in the Hazardous and Solid Waste Amendments of 1984, signed by President Reagan on November 8, 1984. As part of the provisions of Subtitle I of the Resource Conservation and Recovery Act (RCRA), the U.S. Environmental Protection Agency (EPA) was mandated to develop regulations for underground storage tanks (USTs) to reduce the risk of leaks and the resultant risk to human life and property. As part of this regulatory process, EPA was mandated to conduct a national survey of underground storage tanks used to store motor fuel.

The objectives of the national survey are:

1. To provide estimates of the total number of underground motor fuel storage tanks.

2. To provide estimates of the number of establishments with underground motor fuel storage tanks.

3. To provide estimates of the number of such tank systems that leak.

4. To collect information on the characteristics of tanks and tank establishments.

The national survey was to include physical tightness testing for a national probability sampling of tanks. This project provided input to the national survey by evaluating and recommending methods of tank testing.

The objectives of this project were:

1. To select a method for physical testing of underground storage tanks used to store motor fuel to determine if they leaked.

2. To quantify the performance of the recommended method in terms of its precision, accuracy, and suitability for use in a national survey.

3. To define the standard operating procedure of the recommended method for use in the national survey to ensure consistent data of high quality.

In order to achieve these objectives, several guidelines for judging methods of testing tanks were developed. These guidelines related to the performance of the method and to its suitability for use in the national survey. In developing these guidelines, the objectives of the national survey were explicitly considered.

The specific quidelines that were developed for use in the selection process are presented in Section II, Preliminary Investigation. These guidelines include consideration of method performance, the means that each method uses to account for sources of interference to the measurement process (thermal expansion effects, tank deformation, water table, etc.), the imposition on the owner/operator caused by the method, and the availability of equipment and trained personnel to perform the testing needed in the national survey.

In this report, the commonly used term "underground storage tanks" refers to the tank system, which includes the large vessel and all attendant plumbing, fill tubes, distribution lines, vent pipes, and other appurtenances. Thus, the tests evaluated measure the integrity of the system and not just the vessel itself. For regulatory purposes, the definition of an underground tank is one which has 10% of its volume (the vessel together with its associated piping) buried in soil or backfill. The usual case is that the tank and most of its plumbing are buried completely, but the key point is that the system includes both the tank and its piping.

There are also cases where several vessels are included in a manifold system of which there are several types. One important type is a siphon manifold in which two or more tanks are connected by pipes forming a siphon that allows fuel to flow freely from one to the other, thus maintaining the same level in the connected tanks. Such systems may have a single fill pipe and delivery system. Another type of manifolding is that used when tanks are not connected by a siphon but are joined to a common delivery line.

A summary of some of the terms used in this report is provided in Appendix A.

The methods evaluated are for testing tanks used to store motor fuel only. A glossary of fuel names and information about products that were included in the evaluation are found in Appendix B.

English units are used throughout this document rather than metric units because commercial testers measure temperature in degrees Fahrenheit and volumes in gallons. In addition, tank owners, station operators, and others who will use this document operate almost exclusively in English units.

This project was conducted in five phases. Subsequent sections of the report discuss each phase in detail. Section II discusses the preliminary investigations of test methods. Section III discusses the design, testing, and results from preliminary testing of methods in a controlled setting. Section IV presents the experimental approach and results from a field trial of potential methods used to test at a variety of geographic locations and the method recommended for use on the national survey. Section V describes the results of a pilot test of the method recommended for national testing. Section VI is the final set of recommendations for the national survey test procedures. The appendices contain supporting information either too detailed for inclusion or that is peripheral to the purpose of the project.

After the evaluation of a number of test methods (see Appendix C), it is clear that none of the standard test methods evaluated in the program can consistently and reliably achieve detection of the 0.05 gal/h leak rate specified by the NFPA 329, "Recommended Practices for Underground Leakage of Flammable and Combustible Liquids, 1983." This conclusion is based entirely on the data collected during the method selection phase of the program since supporting data which had been requested from the test companies to document their performance claims were not received.

While some methods can provide reliable results under some specific conditions, there are many situations which commonly occur in the test environment (such as the presence of a water table) which can invalidate the test results. Unless the test crew takes specific steps to identify these conditions, the reported results may be either misleading or incorrect. Most test methodologies currently in use fail to take definitive steps to identify one or more of these problem areas. The test results obtained must therefore be suspect to the degree that these factors have not been recognized. The effects of not identifying these conditions can be substantial and, in general, cannot be evaluated from the test data after the test crew has left the test site.

One of the major objectives of the activities carried out prior to the national survey was to identify and characterize a test method suitable for use on the program. The Petro-Tite method was selected as offering the most promising approaches to identifying potential problems and taking action to correct them. Further, it was judged to provide the most consistently reliable data for the national survey. It has stated procedures to identify and correct for tank end deflection, temperature effects, water table, and vapor pockets. The test time and sample frequency were increased in order to improve the precision of the test results and to assist in identifying problem areas when present. These modifications were then characterized during the pilot study phase of the project and a test protocol using the modified technique was developed. This modified Petro-Tite method was then used on the national survey.

II. PRELIMINARY INVESTIGATION

A. Overview

Preliminary investigation into the status of tank testing technology revealed at least 20 methods available for the testing of underground storage tanks. Since both time and funds precluded a thorough evaluation of all these methods, it was necessary to develop a screening process to reduce the number of methods to a manageable level. This screening process involved several steps.

First, a set of general selection guidelines was developed. Second, the methods under consideration were classified into their basic leak detection characteristics and several were selected for further consideration. Third, field observation visits were conducted at seven sites to observe a test demonstration. Finally, five methods were selected for field testing under controlled conditions.

B. General Selection Guidelines

A set of general selection guidelines was developed so that methods which clearly could not provide data which would meet the national survey requirements could be eliminated from further consideration. These guidelines were intended to be somewhat flexible so that even though a particular method might not meet all of the criteria, if potential advantages existed it could still be considered.

The most basic requirements for selecting a method suitable for testing underground fuel storage tanks are those related to sensitivity, accuracy, and precision. However, the practical considerations of the cost of a national survey and the facilitation of access to private tank systems impose several additional requirements. The general method selection criteria used in the preliminary investigation are described below.

1. Quantitative Measurement

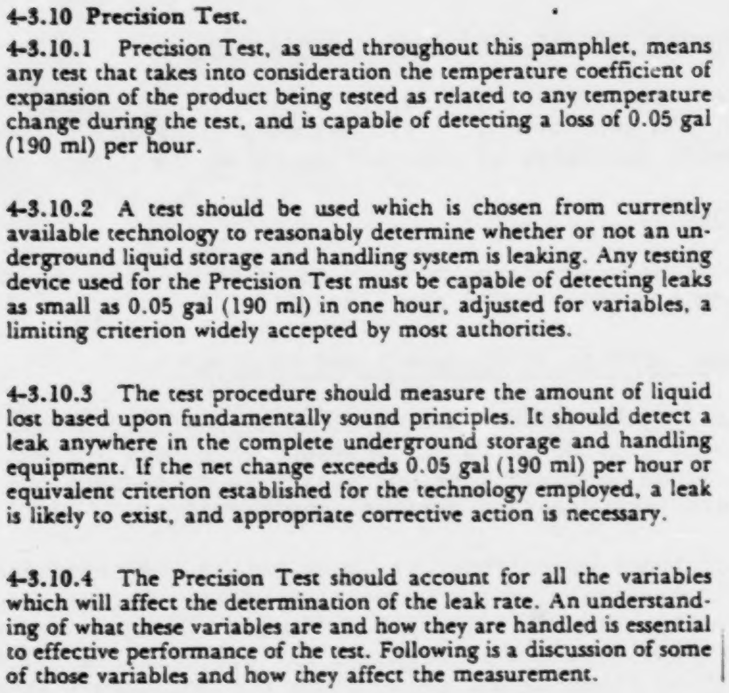
Because one of the objectives of the national survey was to provide an estimate of the amount of fuels leaking from USTs, the method had to provide reliable quantitative determination of leak rates for each system tested. This requirement could have been waived, however, if qualitative methods were found to be significantly more reliable at detecting very small leak rates.

2. Detection Levels

The National Fire Protection Association (NFPA 1983) has established the criteria for precision testing shown in Figure 1. For purposes of this program, 0.05 gal/h was taken as the reference point for comparison of various volumetric methods. However, as described in subsequent sections of this report, highly reliable detection of 0.05 gal/h leaks using existing test procedures may not be achievable for many test methods and for some tank systems. The result of the evaluations conducted in this study was to provide documented performance characteristics for each of the methods tested.

3. Invasiveness

The survey method should cause a minimum of disruption to the operation of the tank system. This criterion was especially important to minimize imposition on the owner/operator and to encourage cooperation with the survey.



4-3.10 Precision Test.

4-3.10.1 Precision Test, as used throughout this pamphlet, means any test that takes into consideration the temperature coefficient of expansion of the product being tested as related to any temperature change during the test, and is capable of detecting a loss of 0.05 gal (190 ml) per hour.

4-3.10.2 A test should be used which is chosen from currently available technology to reasonably determine whether or not an underground liquid storage and handling system is leaking. Any testing device used for the Precision Test must be capable of detecting leaks as small as 0.05 gal (190 ml) in one hour, adjusted for variables, a limiting criterion widely accepted by most authorities.

4-3.10.3 The test procedure should measure the amount of liquid lost based upon fundamentally sound principles. It should detect a leak anywhere in the complete underground storage and handling equipment. If the net change exceeds 0.05 gal (190 ml) per hour or equivalent criterion established for the technology employed, a leak is likely to exist, and appropriate corrective action is necessary.

4-3.10.4 The Precision Test should account for all the variables which will affect the determination of the leak rate. An understanding of what these variables are and how they are handled is essential to effective performance of the test. Following is a discussion of some of those variables and how they affect the measurement.

Figure 1. Precision testing as defined by the National Fire Protection Association, Inc. Source: NFPA 1983.

4. Physical Reliability

The test equipment and procedure should be reasonably rugged and reliable to ensure successful completion of all testing required in the survey.

5. Versatility

The test should be applicable to a wide variety of tank system configurations so that a single method could be used to conduct the entire survey. Since the national survey was intended to include nearly all sizes of service stations, fleet and other commercial refueling installations, and farms, it was likely that numerous configurations would be encountered. The test method should also be applicable to most test situations (e.g., high water tables).

6. Amenability to Performance Monitoring

The test procedure should allow monitoring and assessment of accuracy, precision, and sensitivity. This method performance information was required to provide estimates of the confidence of the survey results.

7. Cost

The cost of conducting the test and interpreting the test results must fit the budget available for the national survey program.

8. Availability of Equipment and Manpower

The ability to conduct the nationwide survey on a timely and cost effective basis was considered to be important. Methods for which sufficient equipment and trained manpower were not available to support the national survey effort were excluded from serious consideration.

Each of these guidelines was important to the selection of a test procedure for the national survey. Since the various methods each operate somewhat differently, they will exhibit different strengths and weaknesses. No one method provides optimum performance for all criteria. The scope of the method selection research and pilot study did not permit exhaustive method evaluation of all available test methods in order to select a procedure with optimum characteristics for all criteria. Hence, some degree of compromise was necessary to proceed expeditiously with the survey.

C. Identification and Classification of Test Methods

The initial literature search identified a number of methods, listed in Table 1, which had been used to test tanks. The review was not exhaustive and drew heavily on presentations at the PACE Symposium (PACE 1982) and the Petroleum Equipment Institute Symposium (PEI 1983) as well as on literature obtained from various test groups. A discussion of each of these methods (and some additional ones) has been compiled in a report on underground tank leak detection methods which was prepared for EPA by the IT Corporation (EPA 1986). While these descriptions are based almost entirely on the suppliers'

Table 1. Leak Detection Methods Reviewed

Detection method	Literature review	Field site visits	Preliminary testing	Development study	Pilot study
Volumetric					
ARCO	X	X	X	X	
Certi-Tec	X	X	X		
Ethyl tank sentry	X				
Ezy-Chek	X				
Petro-Tite tank and line testing system	X	X	X	X	X
Hydrostatic (standpipe) testing	X				
Lasar interferometry	X				
Leak Lokator	X	X	X	X	
Mooney tank leak detector	X				
Pald-2 leak detector	X				
Pneumatic testing (air test method)	X				
Non-Volumetric					
Dye method	X				
Vacutect method	X				
Helium leak detection method	X	X	X		
Tracer Research test	X				
Inventory monitoring					
Manual methods	X				
Automated	X	X			
External monitoring					
Pollulert	X				
Remote infrared sensing	X				
Ground water and soil core samples	X	X		X	
Underground radar	X	X			

information rather than on objective, independent test data, the report provides a useful overview of the tank testing methodology available at the time.

The methods were classified according to their major operational characteristics. The four categories considered were volumetric (quantitative), nonvolumetric (qualitative), inventory monitoring and reconciliation, and external monitoring. Each of these categories is briefly described below.

1. Volumetric Leak Tests

Volumetric leak tests are based on the principle that the change in the volume of fluid in the tank due to a leak can be determined by measuring properties associated with that change in volume. The usual procedure in a volumetric leak test is to measure the product level and product temperature in the tank over a period of time. The level changes are then corrected for the expansion or contraction of the product due to temperature changes. This gives a temperature compensated volume change over the period of the test. The leak rate can then be calculated. The product level is usually measured directly, but other sensors such as transducers which measure changes in pressure at the tank bottom can also be used. The major sources of variability which can affect the test outcome and are common to nearly all the volumetric methods are summarized below.

- Distortions in the tank may occur as the level of product in the tank is changed. Time for stabilization must be provided each time the level is changed significantly. These distortions may be affected by the type of backfill material used around the tank and the presence of a water table. These factors are uncontrollable and will vary widely from tank to tank.

- Temperature changes will cause thermal expansion or contraction of the tank as well as of its contents. Only small temperature changes (on the order of 0.001°F/h for large tanks) are needed to offset or amplify the indicated leak rate. These effects can be corrected for if careful temperature measurements are obtained during the test.

- Pockets of air or vapor trapped in the tank or piping can cause misleading results since the volumetric expansion of gases is much greater than that for liquids. This problem is particularly acute for those test methods which require the tank to be overfilled.

- Vibrations from external sources, such as traffic, can have adverse effects.

- Evaporation and condensation may occur in the tank particularly on hot, windy days and in partially filled tanks. These factors can be controlled or minimized by proper design of the equipment and test procedures.

Some or all of these factors may be operating in any given test. Their effects and the ability of a given test method to compensate for them are often unknown because essential data may be unavailable. Failure to recognize and compensate for these factors can lead to either false positive or false negative results. A discussion of these sources of error is provided in Appendix C.

Since temperature variation and compensation are the most important variables, additional data were collected. A discussion of these data is provided in Section IV.D.1, and temperature behavior studies are included in Appendix D.

Other factors which can affect the sensitivity of a method include the size of the tank, the time available to monitor changes, the time elapsed since the last addition of product to the tank, and the presence of an underground water table in contact with the tank.

2. Nonvolumetric Leak Tests

Several nonquantitative methods are available for qualitatively determining if leaks are present in underground storage tanks. These techniques may be useful for identifying tanks that are leaking, after which the more thorough volumetric tests can be applied.

These techniques rely on measurement of a parameter which is not directly associated with product loss, but rather indicate the presence of a hole. These can include the detection of sound patterns associated with bubbles which are formed when a slight vacuum is placed on the tank or with the presence of helium in the immediate environment around the tank. In some cases, the size of the hole and the leak rate can be estimated.

3. Inventory Monitoring and Reconciliation

a. Manual Record Keeping and Reconciliation

Careful product monitoring can be used as a first step in detecting the existence of a leak. Early detection of leaks can sometimes be achieved by proper product inventory, regular inspection of the visible parts of the product handling system, and prompt recognition of the conditions indicating that leaks may be occurring in the underground tank or piping.

This method of leak detection requires good bookkeeping, is an indirect measure of leaks, and when properly applied, can provide other information useful to the tank owner. Some of the more obvious situations which can be identified are:

- Loss of product in a tank system. For example, loss of product when the product is not being dispensed usually indicates a leaking tank, but it may also indicate faulty accounting or metering of the product, extreme temperature change, or theft.

- An apparent increase in product level. Increases in the product level in an underground tank may be caused by water leaking into the tank if the ground surrounding it is saturated with water. The increase may also be caused by a leaking gauge or fill cap, and these should be examined and made watertight, if necessary, before concluding that the tank is faulty.

- Increasing differences between the amount of product received and the amount dispensed. This may indicate a meter calibration problem, theft, or a leak in tanks or piping.

- Large differences appearing consistently between the amounts invoiced and the tank gauges after deliveries where dispensers are located remotely from the tanks. This may indicate a leak in the remote dispenser line. In such an event, the line should be tested.

A number of factors can make the inventory method uncertain. For example, changes in product temperature can lead to expansion, contraction, evaporation, and condensation of the stored product. Errors can also occur through faulty readings of dipstick measurements. Mathematical errors may also occur which can lead to incorrect conclusions.

b. Automated Methods

There are a number of automated continuous monitors which record the level and temperature in the tank at regular intervals. These are usually microprocessor controlled and can be programmed to perform all of the normal inventory record keeping functions. The measurement methods are varied. While these methods have improved, their general level of sensitivity is usually around 0.2 gal/h.

4. External Monitoring

External monitoring is keyed to the effects produced by hydrocarbon products which have escaped and can give an indirect indication of the presence of a leak. Background concentrations may also result from spills, overfilling, and remote releases from other tanks. In many cases, it is difficult to determine the exact source of the release. These methods do not provide any estimate of the leak rate.

Methods from each category were considered in light of the guidelines, and those felt to represent the best potential for use on the national survey program were identified. There is little doubt that some very good methods were eliminated from further consideration at this stage.

D. Field Observation Visits

After all of the methods listed in Table 1 had been reviewed, the following methods and companies were selected by MRI and EPA personnel for observation in the field.

Method	Company
ARCO HTC	Atlantic Richfield, Harvey, IL
Certi-Tec	Fuel Recovery Company, Inc., St. Paul, MN
Leak Lokator	Hunter Environmental, Inc., Malvern, PA
Petro-Tite	O.H. Materials, Findlay, OH
Helium leak detector	Smith and Dennison, Hayward, CA
Core drilling	National Institute for Petroleum and Energy Research, Bartlesville, OK
Underground radar	Ohio State University, Columbus, OH

Accordingly, visits were arranged for MRI and EPA personnel to observe the methods in actual use. The site visits are described in detail in Appendix E.

Since one of the major objectives was to obtain quantitative results from the testing, four of the methods selected were volumetric. Most volumetric methods rely on measurement of product temperature and level to detect leaks. The four volumetric methods selected have somewhat different hardware configurations and approaches to temperature and level measurements.

The methods observed are described briefly below. They were evaluated for suitability for use on the national survey using the general selection criteria.

The ARCO method utilizes a photo optical sensor to monitor the level of a partially filled tank. If the test conditions are set up properly, the device is self-compensating for temperature changes. Only the portion of the tank containing the product is tested.

The Certi-Tec method uses pressure transducers which are located just below the surface of the liquid to measure level changes. Seven thermistors are used to measure temperature at various levels in the tank during testing. The tank is overfilled during the test by adding an extension to the fill pipe. Both the tank and lines are tested at the same time.

Leak Lokator uses a buoyancy probe to monitor product level with a single thermistor located at the midpoint of the tank. The method can be used to test a partially filled tank (with lower sensitivity) or an overfilled tank. Either the tank or the tank and lines can be tested.

The Petro-Tite method monitors product level visually in an extended fill pipe. The product level is returned to the reference level at 15-min intervals during the test. The product is stirred continuously during the test to achieve a uniform temperature. Temperature is monitored with a single thermistor located at the inlet to the pump near the top of the tank. The tank and lines are all tested at the same time.

The Varian helium leak detection method, a nonvolumetric method, is based on the detection of helium outside a tank which has been slightly pressurized with helium. The tank should be empty during the test if the entire tank is to be tested. It is also helpful to drill a number of small holes in the surface above the tank to assist in the location of the leak. Pressure can be monitored simultaneously to provide a quantitative estimate of the leak rate. The lines are tested at the same time.

Core drilling and underground radar are two external monitoring approaches which were considered. Core drilling involves drilling a number of wells in the area surrounding the tank. The core samples obtained are analyzed for the presence of hydrocarbon using a gas chromatograph or other hydrocarbon sensor. A number of wells may need to be drilled depending on the hydrogeological conditions in the area. No estimate of the rate is possible.

Underground radar depends on the detection of a radar signal which is reflected from differing objects and conditions under the ground. The method has been used to detect leaks in water lines, but has not been used as a hydrocarbon leak detector. The main advantages are that it is nondisruptive, little or no site preparation is needed, and the facility can continue to operate during testing.

The field observation visits were somewhat cursory in nature. No data were obtained for analysis; and in several cases only laboratory type demonstrations were provided, which were inadequate for reliable evaluation of the method in actual field use. Nonetheless, none of the volumetric methods appeared to provide any clear advantages or disadvantages for use on the national survey. Since no data were obtained under controlled conditions, the actual performance characteristics could not be determined. It was decided to evaluate all four of the volumetric methods under controlled field conditions.

The helium leak detector was judged to have potential for use on the national survey partially because the personnel at Smith and Dennison felt that it might be possible to obtain volumetric estimates by using pressure sensing equipment they had developed in conjunction with the helium leak detector. The method demonstrated some potential for providing quantitative results, although there were some problems with the pressure measurement part of the test. The method was observed to be extremely sensitive and did locate what appeared to be leaks in both the lines and the tank, so it was decided to evaluate this test method further.

Although core drilling and underground radar both provide useful information about leaking tanks, both were eliminated due to their limitations. Two of the major limitations of core drilling were considered to be its inability to provide leak rates and the ambiguity of the results in identifying the specific source of the hydrocarbons. Since one of the primary objectives was to estimate the number of leaking tanks, the latter limitation was considered particularly serious. The state of development of underground radar for use as a hydrocarbon leak detector precluded its use in the near term. The interpretation of the test results is relatively complex and the availability of test equipment is very limited.

Since inventory reconciliation was to be evaluated in another part of the national survey, these methods were not considered for use as leak detectors on this project. One automated unit manufactured by Veeder-Root was observed during the site visits, however.

III. PRELIMINARY TESTING

The primary objectives of the preliminary testing were as follows:

1. To develop the evaluation procedure to be used on later phases of the program. The leak simulation procedures were of particular importance.

2. To evaluate the ability of each test method to track a series of simulated leaks using normal test procedures. (accuracy)

3. To evaluate the ability of each method to obtain repeatable results when given the same leak rate. (precision)

4. To screen out any methods which would not be suitable for use on the national survey. The general selection guidelines were used for this purpose.

Preliminary testing was performed at a Kansas City, MO, service station that was no longer in operation but still had underground storage tanks. The subject tank was constructed of steel and had a nominal capacity of 7,400 gal. The tank was filled with regular gasoline for the testing. The product remained generally undisturbed in the tank for several weeks during the testing. Some product was added or removed from the tank to meet the requirements of the particular test method. Testing was done during July and August, making it more likely that the ambient temperatures would produce thermal stratification in the tank for those tests that did not stir the product. External interferences with the level in the tank were generally minimal, however, probably less than would usually be encountered at a station in normal operation. Because all the methods tested found that the tank did not leak, it was concluded that the test unit was a tight tank.

A. Experimental Procedure

1. Evaluation Design

Each method was evaluated by testing over a 2- to 3-day period. During the evaluations, each test method was operated using normal procedures. For the quantitative methods, leaks were simulated using a leak simulation system designed and fabricated by MRI. Four different leak rates were simulated in random order for each test method. The simulated leak rates were not disclosed to the test operators until all tests were completed to avoid operator bias. Each simulated leak rate was run for the normal length of a standard test. At the conclusion of the test, when the test operator indicated sufficient data had been collected, a new leak rate was established. In a few cases for tests where water leaks into the tank would be possible under conditions of high water table (ARCO and Leak Lokator), fuel was pumped into the tank to simulate a leak-in condition.

2. Leak Simulation Procedure

a. Description

The leak simulation system, shown in Figure 2, consists of a peristaltic pump, flow meter, and a collection bottle. Product was withdrawn from the tank system at a controlled rate with the peristaltic pump. The flow meter was used to adjust the pump to the selected nominal simulated leak rate. The actual rate was determined at the completion of the test by measuring the product collected in the bottle. During the preliminary method testing conducted at the service station site, the withdrawn product was measured volumetrically using a graduated cylinder. However, for the subsequent development study testing, the withdrawn product was measured gravimetrically. The collection bottles were tared before the test and were reweighed at the conclusion of the test. The volume, corrected to 60°F, was calculated from the total mass and the fuel density.

b. Precision

The precision of the simulated leak rates can be calculated from the precision of the measurements used to calculate the simulated leak rates. In the preliminary testing, the leak simulations were measured by collecting the product and measuring its volume in a graduated cylinder. The precision of this measurement was ± 0.5 mL. The time period used varied, but was the same as the testing method used. In no case was the time less than 5 min. Generally, the minimum volume measured was 10 mL.

One can assume that volume is measured to ± 0.5 mL and that any error is a rounding error, with the uniform distribution. The variance of a uniform distribution with range R is $R^2/12$. The 0.5 mL is converted to gal to express it in the same units as the product is usually measured in. Using the formula gives a variance of $v = 5.8156 \times 10^{-9}$ gal squared, or a standard deviation of 7.626×10^{-5} gal.

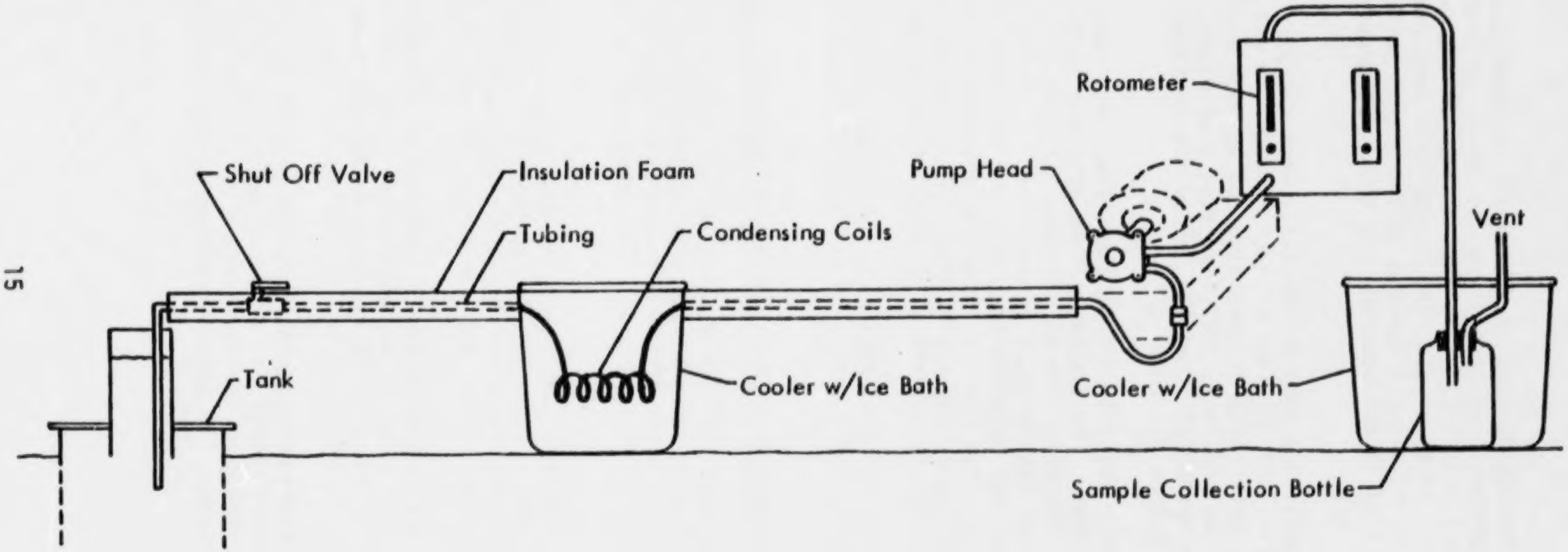


Figure 2. Leak simulation system designed and fabricated by MRI.

For the simulations conducted in the development study phase, mass instead of volume was used to measure the amount of product removed from the tank during leak simulations. The mass determinations were made to ± 0.1 g, which converts to 0.14 mL of gasoline. With this more precise method of determining the amount of product removed during a test period, the variance is reduced to 4.556×10^{-10} gal squared, and the corresponding standard deviation is 2.135×10^{-5} gal.

The data from each of the tests were analyzed statistically to determine the precision and accuracy of each method. An estimate of the accuracy (or bias) was determined by obtaining the average difference between the leak rates reported and the actual simulated leak rates. A paired t-test was used to test the hypothesis that the method was unbiased; that is, that the mean signed difference was zero.

A linear regression of the observed leak rate on the simulated leak rate was calculated. The scatter of the data around the regression line was used to estimate the precision of the test. A test which is operating properly is expected to have a slope of one; that is, there is a one-to-one correspondence between the observed leak rate and the simulated rate. A slope differing significantly from one indicates the presence of some interfering factor which is operating during the testing. Plots of the data for each method have been provided in subsection B, Results, which follows.

The bias and precision were then combined to obtain an estimate of the root mean squared (RMS) error, an estimate of the overall performance of the test method.

c. Comparison with Volumetric Method Precision

To evaluate the leak simulation results, it is helpful to assess the relative accuracies of the leak simulations and the tank testing methods. A general calculation of the variance associated with a typical tank test has been provided for this purpose. The comparison is based on worst case conditions.

The volumetric tank tests are most precise when used on small tanks. The smallest tank of interest in the national survey is 250 gal. This volume is used to calculate the precision associated with a tank test for comparison with the precision of the leak simulation derived above.

There are two measurements made for a volumetric test. One of these is temperature, the other is volume change. Both are relative to a given time period, which is taken to be the same as that used for the leak simulation measurement of volume, i.e., no less than 5 min.

Temperature measurements are not usually more precise than ± 0.001°F. A temperature change (or rounding error) is converted to an equivalent volume by multiplying by the coefficient of thermal expansion and then by the volume of the tank. The product considered was gasoline with a thermal expansion coefficient of approximately 0.00062/gal and /°F. Thus, 0.001°F converts to volume as

$$V_G = 0.001 \times 0.00062 \times 250 = 1.55 \times 10^{-4} \text{ gal}$$

for gasoline. Again, a uniform distribution is assumed for rounding errors in measuring temperature to calculate the variances in these determinations as

$$v^2_G = 8.008 \times 10^{-9} \text{ gal squared}$$

for gasoline. The corresponding standard deviation is 2.685×10^{-4} gal for gasoline.

The level is measured in a graduated cylinder and is reported to the nearest 0.001 gal. Again, assuming the uniform distribution for the rounding error, the variance for the volume determination is calculated as

$$v^2_{vol} = \frac{(2 \times 0.001)^2}{12}$$

$$= 3.337 \times 10^{-7} \text{ gal squared}$$

This corresponds to a standard deviation of 5.77×10^{-4} gal. The total variance for a determination of a temperature corrected volume for a single period (5 min) is the sum of the variance of the volume and temperature measurements. This becomes

$$v = 3.413 \times 10^{-7} \text{ gal squared}$$

The corresponding standard deviation is 5.84×10^{-4} gal

Comparison of these values with the standard deviation for the leak simulation volume determination, namely 2.135×10^{-5} gal, shows that the error in the leak simulations is an order of magnitude smaller than the calculated error in the testing measure. In addition, comparison of the errors calculated for the leak simulation with the empirical RMS values for each method indicates that under actual use conditions the simulations are three orders of magnitude smaller. Thus, the error in the leak simulation volume rates can be ignored.

B. Results

A summary of the statistical analysis for the quantitative methods as a group is presented in Table 2. Following that table is a brief discussion of the statistical results of each method, accompanied by its respective data table and plot of the data.

Table 2. Summary of Statistical Analysis of Quantitative Methods Tested at Kansas City Service Station Site

Method	n[a]	Bias (gal/h)	Intercept (gal/h)	Slope	Standard error (gal/h)	RMS (gal/h)	R^2 (%)
ARCO	15	-0.01	0.005	0.95	0.049	0.050	94.3
Certi-Tec	12	+0.25	-0.30	0.71	0.166	0.302	38.9
Leak Lokator	22	+0.01	-0.01	0.94	0.020	0.021	98.9
Petro-Tite	18	+0.05	0.06	1.05	0.101	0.113	75.9

[a] Number of simulated leaks.

1. ARCO Method

The ARCO method was tested using 15 simulated leak rates, including one zero rate. An average difference of 0.01 gal/h was observed between the rates reported by ARCO and those calculated by MRI. This estimated bias in the results was not significantly different from zero ($t = 0.21$, 14 degrees of freedom). The estimated regression of the observed leak rates on the simulated leak rates was

$$Y = 0.005 + 0.943 X,$$

where Y is the leak rate reported by ARCO and X is the leak rate simulated by MRI. The ideal regression equation (in a tight tank) would be

$$Y = 0.0 + 1.0 X.$$

With the ARCO method, the intercept did not differ significantly from zero and the slope did not differ significantly from one. The data are displayed in Table 3 and plotted in Figure 3. The R^2 for the regression was 94.3%, indicating that most of the variability of the data was explained by the regression. The RMS error estimated for the method under the conditions of the Kansas City test was 0.05 gal/h. This is the estimated variability associated with a single test. In this case, each test averaged just under an hour (55.7 min) in duration. In order to reduce the variability estimated with the method, either repeated determinations or a longer test time would be needed. Repeated determinations of a leak rate under the same conditions would reduce the variance by a factor of $1/n$, where n is the number of determinations. It is not clear how much variability would be reduced if the test time were increased for a single reported leak rate.

2. Certi-Tec Method

The Certi-Tec method was tested using 12 simulated leak rates, of which two were set at zero and so represented the normal condition of a tank test. The results of the Certi-Tec test evaluation are presented in Table 4 and displayed graphically in Figure 4. The leak rates reported by the Certi-Tec method took slightly over an hour (average 64.3 min) for each rate. The estimated bias in the results (difference between the reported rate and the simulated leak rate) averaged -0.25 gal/h. That is, the reported leak rates were estimated to be too large (too much product leaking) by about a quarter a gallon per hour. This bias was quite large and was significantly different from zero ($t = -5.23$, 11 degrees of freedom). The estimated regression of the leak rates reported by the method on the simulated leak rates was

$$Y = -0.30 + 0.71 X,$$

where Y is the leak rate reported by Certi-Tec and X is the leak rate simulated by MRI. This differs substantially from ideal. In fact, the intercept differs from zero at the 5% significance level and the slope differs from one at the 5% significance level as well. The standard error of the regression was 0.167 gal/h. The R^2 of the regression was only 38.9%, indicating that slightly less than 40% of the variability in the reported leak rates was explained by the simulated leak rates used in the test.

Table 3. Results Summary from ARCO

ARCO leak rate (gal/h)	MRI test		
	dTime (min)	dVolume (mL)	Leak rate (gal/h)
-0.140	85.0	-660.0	-0.123
-0.080	90.0	-485.0	-0.085
-0.460	60.0	-1,895.0	-0.501
-0.070	77.0	-635.0	-0.131
-0.210	45.0	-625.0	-0.220
-0.100	69.0	-390.0	-0.090
0.040	37.0	0.0	0.000
-0.050	61.0	-215.0	-0.056
-0.130	54.0	-115.0	-0.034
-0.250	60.0	-785.0	-0.207
0.210	29.0	370.0	0.202
-0.060	60.0	-150.0	-0.040
-0.490	32.0	-1,150.0	-0.570
0.240	47.0	430.0	0.145
-0.030	30.0	-41.0	-0.022

Bias -0.010 gal/h Test (Bias = 0) t = -.21 Non-significant
RMS 0.050 gal/h

Regression Y = -0.005 + 0.952 (Sim)

R-Squared = 0.943 Standard error (SE) = 0.049

$SE(B_0) = 0.0148$ $SE(B_1) = 0.0647$

95% Confidence interval for B_0 (-0.028, 0.036)
95% Prediction interval at 0 (-0.107, 0.115)

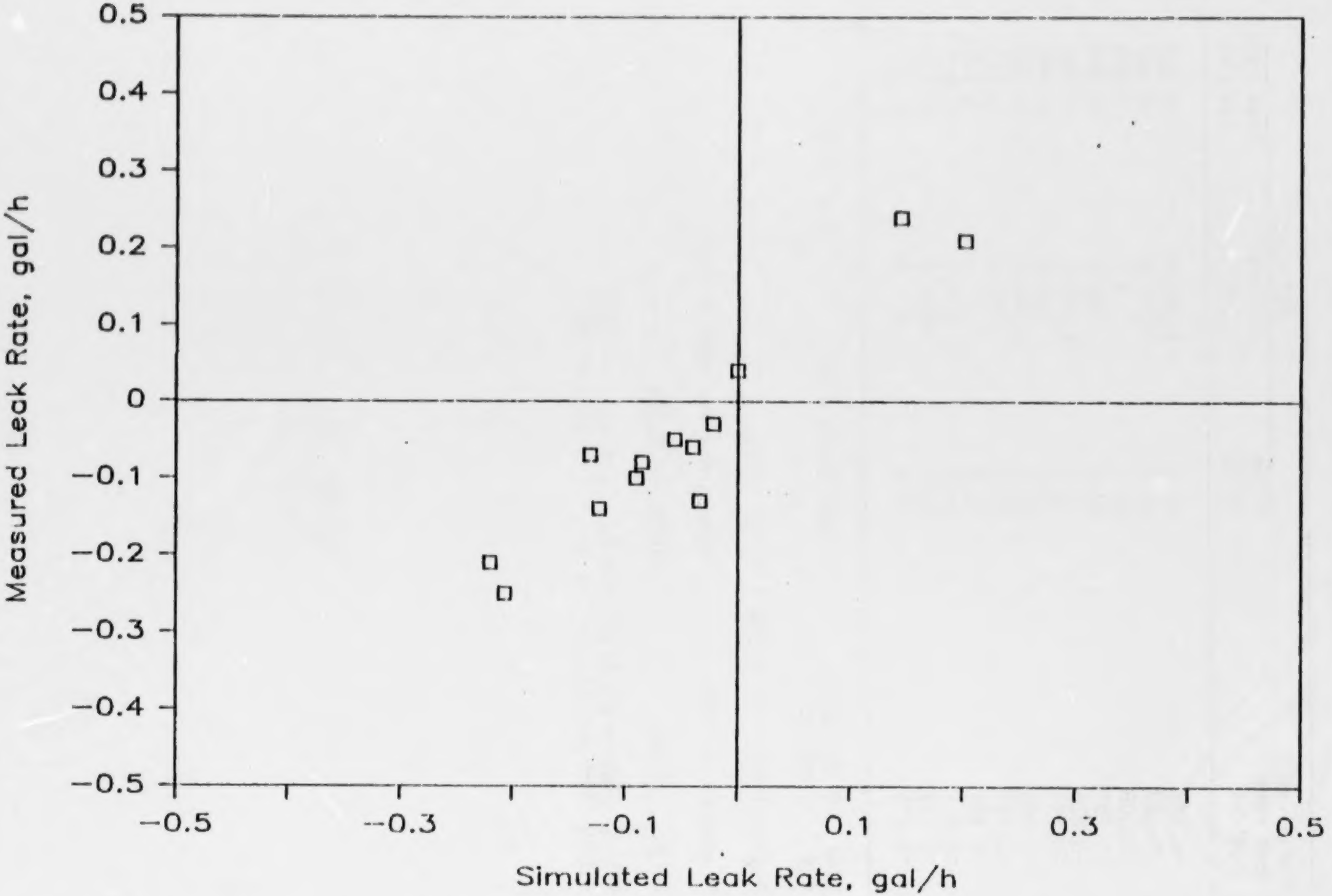


Figure 3. ARCO test - measured leak versus simulated leak. (Positive values represent leaks in.)

Table 4. Results Summary from Certi-Tec

Certi-Tec leak rate (gal/h)	MRI test dTime (min)	MRI test dVolume (mL)	MRI test Leak rate (gal/h)
-0.446	41.0	-1,345.0	-0.520
-0.687	82.0	-710.0	-0.137
-0.506	90.0	0.0	0.000
-0.255	85.0	-309.0	-0.058
-0.428	91.0	-1,180.0	-0.206
-0.350	90.0	-240.0	-0.042
-0.883	60.0	-1,930.0	-0.510
-0.468	53.0	-760.0	-0.227
-0.188	60.0	0.0	0.000
-0.222	60.0	-195.0	-0.052
-0.318	30.0	-270.0	-0.143
-0.276	30.0	-210.0	-0.111

Bias -0.251 gal/h   Test (Bias = 0)   t = -5.23
RMS 0.301 gal/h

Regression Y = -0.300 + 0.710 (Sim)

R-Squared = 0.389   Standard error (SE) = 0.166

$SE(B_0) = 0.067$ $SE(B_1) = 0.282$

95% Confidence interval for B_0 (-0.450, -0.150)
95% Prediction interval at 0 (-0.700, 0.099)

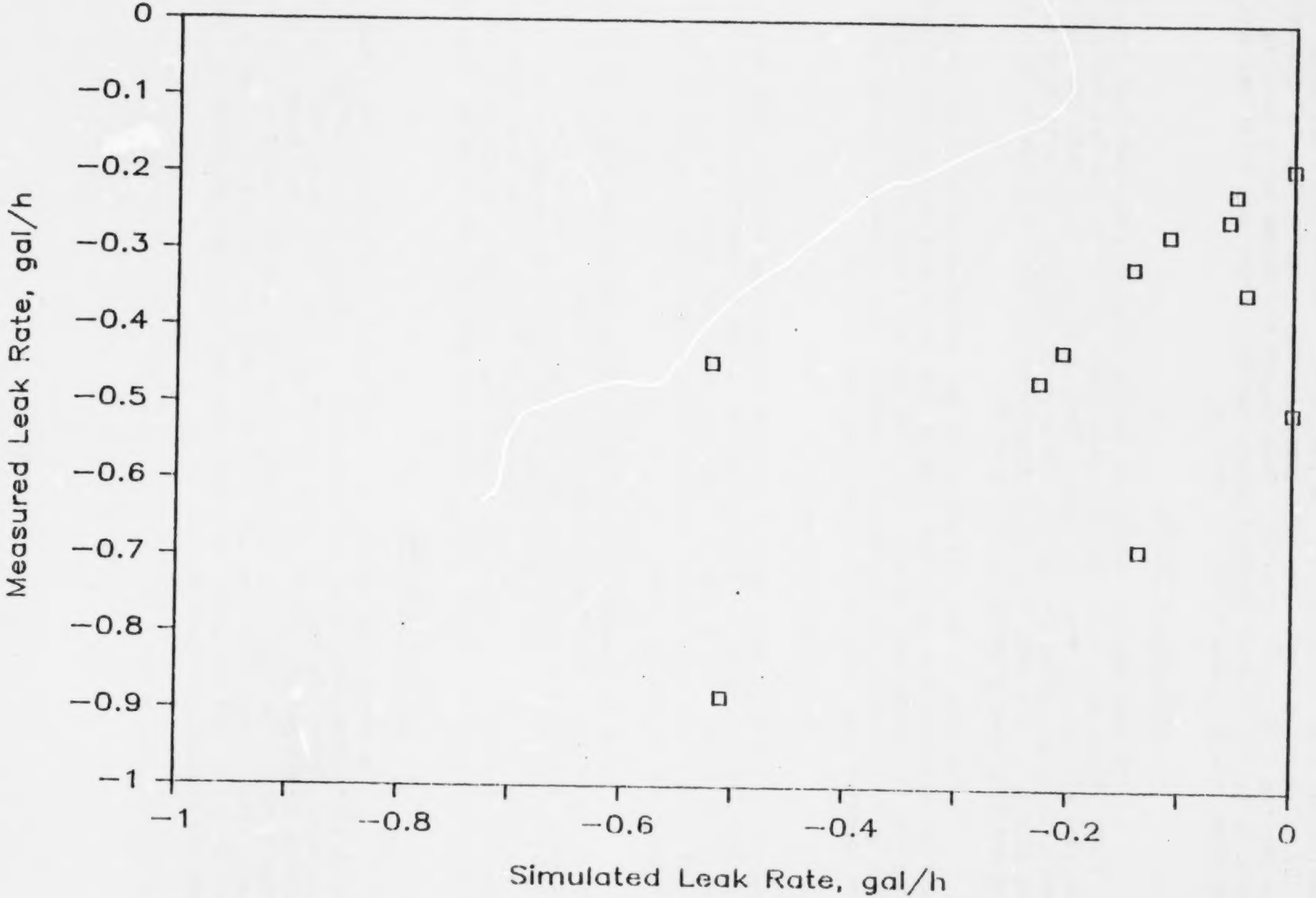


Figure 4. Certi-Tec test - measured leak versus simulated leak. (Positive values represent leaks in.)

Thus, this method, as implemented during this test, appears to have substantial bias and relatively low precision. The precision estimated at 0.167 gal/h for a single leak rate determination is quite high relative to the desired 0.05 gal/h criterion. Even though the random error could be reduced by taking several repeated determinations of the leak rates and averaging them, the bias would remain a problem.

3. Leak Lokator Method

The Leak Lokator method was tested using 22 simulated leak rates. Of these, three were zero simulated leak rates and so represented tests of the tank without any simulated leak. Three simulated leaks into the tank were also used. Using the method, the average reported leak rate duration was 10.8 min. The data from these determinations are presented in Table 5 and are displayed graphically in Figure 5.

The bias in the determinations was estimated to be -0.005 gal/h. That is, the reported leak rates (out of the tank) were very slightly higher than the simulated leak rates. This bias was not significantly different from zero (t = -0.23, 21 degrees of freedom). The estimated regression of the reported leak rates on the simulated leak rate was

$$Y = -0.012 + 0.935 X$$

where Y is the leak rate reported by Leak Lokator and X is the leak rate simulated by MRI. The R^2 for the regression was 98.9% and the standard error was 0.020 gal/h. The estimated slope and intercept agree closely with the ideal values, but both differ from the ideal significantly at the 5% level, although not at the 2% level.

These data showed a very small scatter about the regression line, resulting in small estimated values for the standard error of the slope, intercept, and regression. These small standard errors led to the borderline significances of the difference between the regression parameters and their theoretical values. In light of the nonsignificance of the other test for the bias and the small magnitude of both the intercept (-0.012 gal/h) and the bias (-0.005 gal/h), these significances are probably not of major importance.

4. Petro-Tite Method

The Petro-Tite method was tested under 18 simulated leak rates, of which three were zero rates, corresponding to a tight tank situation. While the usual Petro-Tite test takes an average of four leak rates, each reported over a 15-min period, only five of the 18 determinations were based on an hour's data. The remaining leak rates reported were each based on a 30-min test. The average test time was thus 38.3 min, but, as noted, either a 30-min or a 1-h test was used. The data from the tests are presented in Table 6 and are plotted in Figure 6.

Table 5. Results Summary from Leak Lokator

Leak Lokator leak rate (gal/h)	MRI test		
	dTime (min)	dVolume (mL)	Leak rate (gal/h)
-0.430	12.0	-340.0	-0.449
-0.069	18.0	-84.0	-0.074
0.159	20.0	258.0	0.205
-0.182	14.0	-166.0	-0.188
-0.081	8.0	-39.0	-0.077
-0.072	10.0	-46.0	-0.073
-0.037	16.0	-40.0	-0.040
-0.008	12.0	0.0	0.000
-0.551	13.0	-445.0	-0.543
-0.141	12.3	-98.0	-0.127
-0.238	9.5	-124.0	-0.207
0.054	6.0	31.0	0.082
-0.031	8.5	-19.5	-0.036
-0.170	10.0	-79.0	-0.125
0.005	10.0	0.0	0.000
-0.467	7.0	-235.0	-0.532
-0.084	8.0	-34.0	-0.067
-0.154	6.5	-61.0	-0.149
-0.034	9.0	-21.0	-0.037
-0.005	10.0	0.0	0.000
0.201	7.0	95.0	0.215

Bias 0.005 gal/h Test (Bias = 0) t = 0.23 Non-significant
RMS 0.023 gal/h

Regression Y = -0.012 + 0.935 (Sim)

R-Squared = 0.989 Standard error (SE) = 0.020

$SE(B_0) = 0.005$ $SE(B_1) = 0.022$

95% Confidence interval for B_0 (-0.023, -0.002)
95% Prediction interval at 0 (-0.055, 0.031)

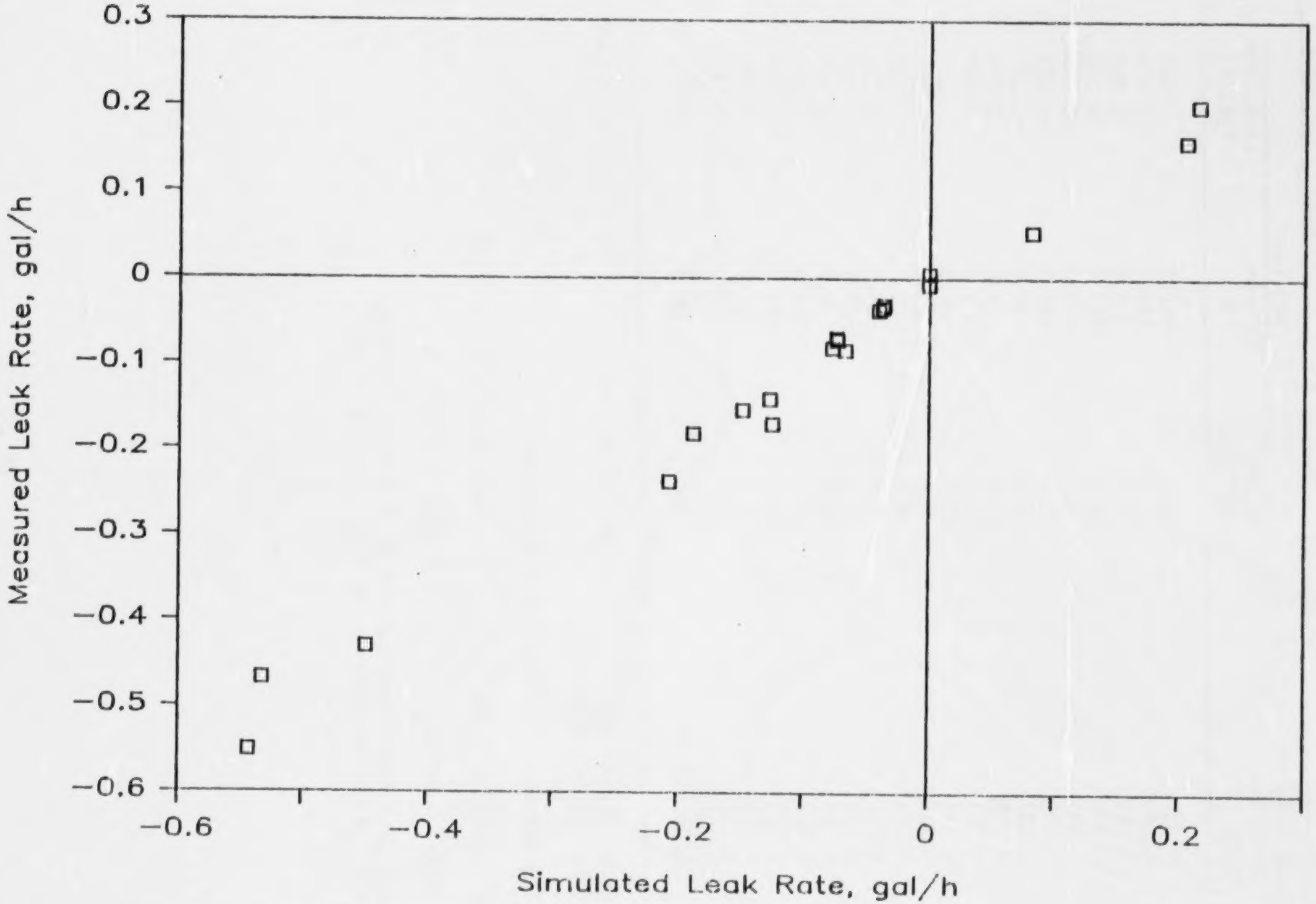


Figure 5. Leak Lokator test - measured leak versus simulated leak. (Positive values represent leaks in.)

Table 6. Results Summary from Petro-Tite

Petro-Tite			MRI test		
dTime (min)	dVolume (gal)	Leak rate (gal/h)	dTime (min)	dVolume (mL)	Leak rate (gal/h)
30.0	-0.342	-0.684	30.0	-1,060.0	-0.560
30.0	-0.030	-0.060	33.5	-295.0	-0.140
60.0	0.046	0.046	59.5	-123.0	-0.034
60.0	-0.220	-0.220	60.0	0.0	0.000
60.0	-0.119	-0.119	60.0	-228.0	-0.060
60.0	0.060	0.060	60.0	0.0	0.000
60.0	-0.080	-0.080	57.0	-718.0	-0.200
30.0	-0.040	-0.080	23.0	-205.0	-0.141
30.0	-0.080	-0.160	27.0	-360.0	-0.211
30.0	0.025	0.050	28.0	-78.0	-0.044
30.0	0.020	0.040	29.0	-105.0	-0.057
30.0	0.000	0.000	32.0	-305.0	-0.151
30.0	-0.225	-0.450	31.0	-1,031.0	-0.527
30.0	0.010	0.020	30.0	-128.0	-0.068
30.0	0.015	0.030	30.0	0.0	0.000
30.0	-0.030	-0.060	26.0	-350.0	-0.213
30.0	0.020	0.040	28.0	-140.0	-0.079

Bias 0.051 gal/h Test (Bias = 0) t = 2.18 Non-significant
RMS 0.108 gal/h

Regression Y = 0.057 + 1.045 (Sim)

R-Squared = 0.759 Standard error (SE) = 0.101

SE(B_0) = 0.033 SE(B_1) = 0.152

95% Confidence interval for B_0 (-0.02, 0.120)
95% Prediction interval at 0 (-0.176, 0.276)

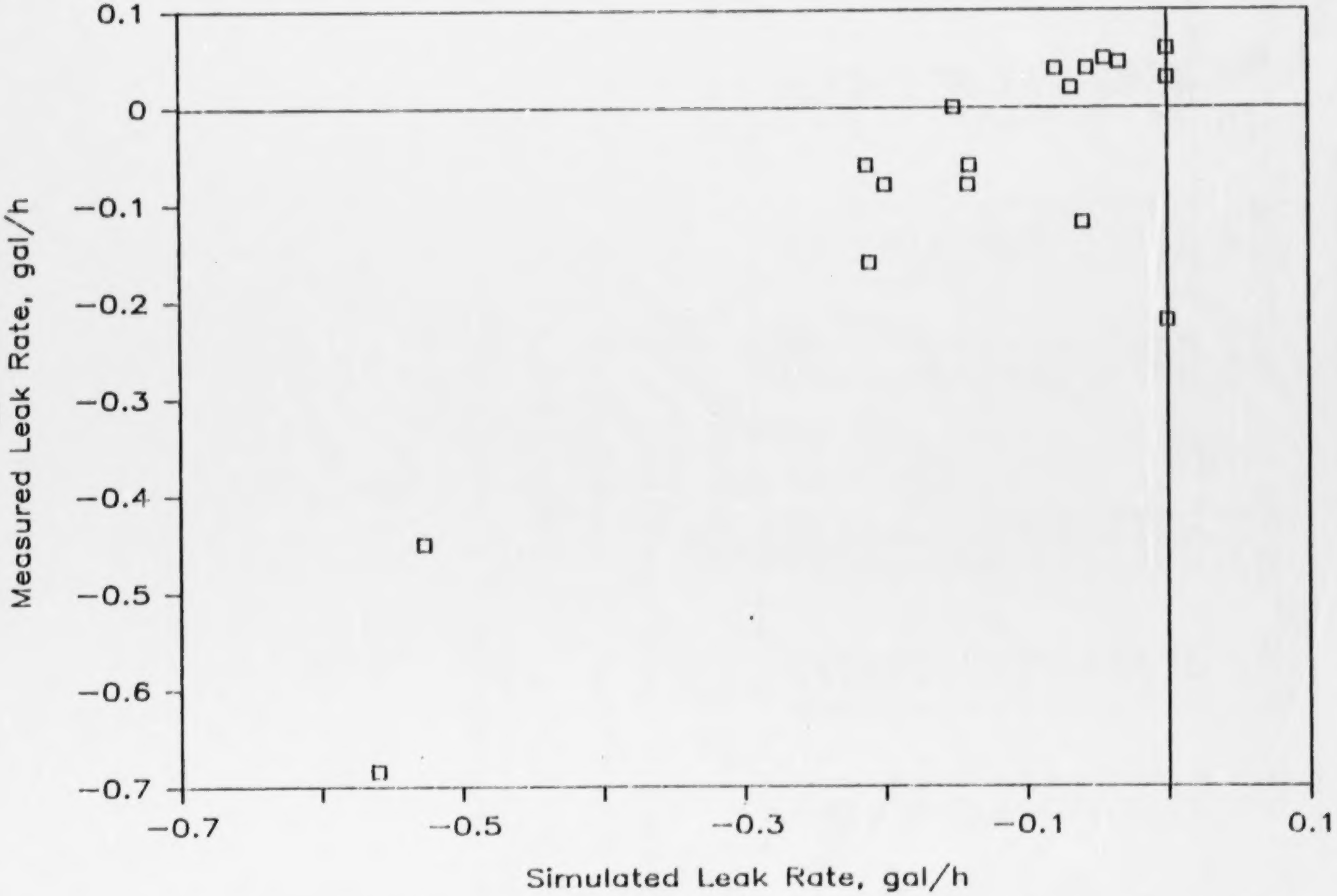


Figure 6. Petro-Tite test - measured leak versus simulated leak. (Positive values represent leaks in.)

From all the tests, the bias was estimated at 0.05 gal/h but was smaller (0.040 gal/h) when restricted to the hour-long tests. The bias from the complete set of tests is almost significantly different from zero at the 5% level. If attention is restricted to the 1-h tests, the bias is clearly not significantly different from zero. The estimated regression of the leak rates reported by the method on the simulated leak rates was

$$Y = 0.057 + 1.045\ X,$$

where Y is the leak rate reported by Petro-Tite and X is the leak rate simulated by MRI. The intercept is not significantly different from zero, suggesting that the bias is not statistically significant. The slope does not differ significantly from the ideal or theoretical value of one. Both of these tests were done at the 5% significance level. The R^2 for the regression was 75.9% and the standard error of the regression was 0.101 gal/h. This standard error is interpreted as the precision of a single leak rate determination. It should be noted that the normal test with four consecutive 15-min rate determinations would be somewhat more precise than what was reported, and that precision could be improved further by testing for a longer period of time and averaging more individual leak rates.

5. Helium Detection Method

Two tests were conducted using the helium detection method. In the first, the tank was tested in its original state. Large leaks were discovered at the remote pump, a 4-in. capped nipple, and the fittings where the test apparatus had been installed in the tank. These leaks were repaired and the results of the next day's test revealed substantial reduction in helium loss at these points.

While some helium was detected around the tank, the amounts were generally very small and could have come from pipe fittings or bungs. Low levels were encountered at the southeast corner of the tank. The concrete was removed for inspection purposes to see if a line was located in that area. None was found. It was concluded that the tank did not have any significant leaks.

An attempt was made to estimate the leak rate by observing pressure loss from the tank using a differential pressure monitor. While this approach may have some merit, the results of the pressure monitoring were erratic due to the temperature sensitivity of the transducer used. Without additional development, this approach would not be satisfactory for the purposes of the national survey.

The primary disadvantage of the helium detection method is its extremely high sensitivity. Helium can escape in measurable quantities even through threaded connections which have not been completely coated with sealer. Gasoline will not normally pass through such connections under operating conditions. Hence, there is a high probability of false alarms with this method. In addition, the results are not quantitative. Since the preliminary assessment of the quantitative methods indicated they had considerable promise for achieving reliable leak rate quantification, the helium method was eliminated from further study.

C. Conclusions and Recommendations

A comparison of the data from the four volumetric methods (shown earlier in Table 2) indicates that the Certi-Tec method performed relatively poorly. Poor performance may have been due to the fact that the method was still somewhat in its development stage, but this method was eliminated from further consideration.

Of the three remaining methods, Petro-Tite had the poorest performance characteristics, probably due to the fact that the test crew conducted a number of 30-min tests as opposed to the standard 1-h tests. The method was retained for further evaluation, in part because of its extremely wide use and long history.

Both the ARCO and Leak Lokator methods performed well under the controlled conditions of the test. The conditions were somewhat favorable in that the product had a long stabilization time prior to the testing.

In evaluating each of these four volumetric methods against the selection guidelines, none of them appeared to present a clear advantage. Very few problems were encountered. Since the tank system was a simple one with all of the distribution lines capped off, most of the problems associated with site preparation were eliminated.

In brief, comparative evaluations of the volumetric methods against the selection criteria revealed the following:

1. Quantitative Measurement

All of the methods tested except the helium method provided quantitative estimates of the leak rate.

2. Detection Levels

Some questions were raised as to how reliably the leaks of 0.05 gal/h could be detected, particularly for the Certi-Tec method. It was dropped from further consideration primarily for this reason.

3. Invasiveness

This parameter was not evaluated at the preliminary testing site except that the three crews demonstrated the capability to set up, conduct the tests, and restore the site in less than a full day. The Leak Lokator method required the least test time and ARCO the longest.

4. Physical Reliability

All four methods were rugged enough to be acceptable. No mechanical problems were encountered.

5. Versatility

This parameter could not be evaluated based on only one test site.

6. Amenability to Performance Monitoring

Performance of all four methods could be monitored satisfactorily.

7. Cost

None of the approaches presented any significant cost advantages at this early stage of evaluation.

8. Availability of Equipment and Manpower

All three companies were national and had sufficient resources to conduct a national survey if selected.

Based on the observations discussed in this section and summarized above, the ARCO, Leak Lokator, and Petro-Tite methods were selected for further evaluation.

IV. DEVELOPMENT STUDY TESTING

A. Overview

The primary objective of this phase of the study was to collect and analyze sufficient data from the three methods selected from the preliminary testing to characterize and compare them. The data would also be used to indicate where modifications might be made in the method selected for use on the national survey.

To accomplish this objective, tank test experiments were undertaken at five sites across the United States using the three test methods. Two types of tests were conducted. The first required the tank test crew to use the standard protocol of that test method. After this test was complete, the crew was requested to estimate the magnitude of different leaks produced by a pump that removed the product from the tank at a known, constant rate. These data were analyzed to estimate the simulated leak rate and to estimate the magnitude of the ambient volume changes over longer test times. The ambient time series was generated by subtracting the simulated leak from the volume measurements. The instrument performance, test protocol, test time, data analysis and compensation procedures, detection criterion, and detection performance were evaluated using a case study approach, because the data on leaking and nonleaking tanks were limited to less than 10 tank tests per method. An extensive analysis of the Petro-Tite data provided by O. H. Materials and of the Leak Lokator data provided by Hunter Environmental Services was performed by Vista Research and MRI. A detailed analysis of the ARCO test method data was not undertaken because ARCO (for proprietary reasons) did not disclose their test procedure and analysis algorithms, or provide the raw data necessary for analysis.

Testing was conducted at the five facilities listed in Table 7. A summary of the characteristics of each tank tested is given in Table 8, and a matrix of the tests conducted is given in Table 9. The facility diagrams, tank characteristics, and test conditions are provided in Appendix G.

B. Method Descriptions

The three methods tested during the development study phase of the project are described in this subsection. The descriptions are based primarily on MRI's observations rather than on manufacturer literature. An effort was made to represent the equipment in light of its performance during the study.

1. ARCO

The ARCO leak test method uses a specially fabricated float mechanism and spectrophotometer to detect volume changes in underground storage tanks and their distribution lines. A schematic of the apparatus is shown in Figure 7. To assure reliable test results, product levels must be between 66 and 75% of the tank depth. The float apparatus, consisting of a cup of dye solution and a photocell, is inserted into the tank at the beginning of the test. The fill port must be at least 3 in. in diameter. The float is placed at a prespecified level in the tank, where temperature changes will not affect the float level. A 1-h waiting period is recommended to allow the temperature of the equipment to stabilize.

With changing product levels, the float rises or drops in the tank and changes the depth of a dye solution between the photocell and a light source mounted on the probe. The change in light transmittance is detected by the photocell according to Beer's Law. Hence, the change in detector response is a function of the change in the product level in the tank. The results are recorded on a strip chart.

The instrument response is calibrated by adding known volumes of product to the tank. The attendant response on the strip chart is used to determine the sensitivity of the device in terms of gallons per division.

The unique feature of the ARCO leak test is that it is self-compensating for temperature changes if the float is positioned properly. (The method may still be sensitive to unstable temperature conditions, but a separate temperature correction is not needed.) The procedure takes advantage of the relationship between liquid density (a function of temperature), liquid buoyancy (a function of density), and liquid volume to select a point where the effect of changes in level due to temperature are exactly offset by changes in buoyancy.

A disadvantage is that the test must be conducted with the tank only 66 to 75% full; therefore, it is not possible to detect leaks in the upper 25% of the tank.

Table 7. Development Study Test Facilities

Facility	Location
Damneck Naval Combat Training Center	Virginia Beach, VA
Pitstop	(confidential)
Scott Air Force Base	Belleville, IL
Fort Lewis	Tacoma, WA
Langley Air Force Base	Hampton, VA

Table 8. Tanks Tested and Their Characteristics

Facility	Tank	Nominal capacity (gal)	Diameter (in.)	Approximate overburden (in.)	Petroleum product
Damneck	1	5,000	96	24	Regular gasoline
Pitstop	1 (south)	12,000	108	38	Regular gasoline
Pitstop	2 (north)	8,000	96	53	Regular gasoline
Scott	1 (17)	5,000	96	44.5	Regular gasoline
Scott	2 (18)	5,000	96	44.5	No. 2 Diesel fuel
Fort Lewis	1 (8C25 north)	12,000	96	10	Unleaded gasoline
Fort Lewis	2 (8C25 south)	12,000	96	5	Unleaded gasoline
Fort Lewis	3 (4194)	12,000	96	22	No. 2 Diesel fuel
Fort Lewis	4 (10E10)	12,000	96	4	Unleaded gasoline
Langley	1 (hydrant system tank 3)	25,000	124	12	JP-4 jet fuel
Langley	2 (hydrant system tank 5)	25,000	124	15	JP-4 jet fuel
Langley	3 (MoGas)	10,000	90	20	Regular gasoline
Langley	4 (golf course)	1,000	49.5	12	Regular gasoline

Table 9. Matrix of Tests Conducted

Facility	Tank	ARCO	Leak Lokator	Petro-Tite
Damneck	1	T[a]	T	T
Pitstop				
South		T	T: Noisy (vibration), possible vapor	T
North		T	T	T
Scott				
17	1	Out of time	T	T
18	2	T	T: Manifold (?)	T
Fort Lewis				
8C25 north	1	T	T: Leak at about gasket; couldn't test	--
8C25 south	2	T	T	T
4194	3	--	T: Poor sensitivity (-0.171)	Added 400 gal; couldn't fill up (bad leak?)
10E10	4	--	T: Results questionable	T
Langley				
HS tank 3	1	--[b]	T: Multiple leaks, plumbing problem	Would have had similar problems if testing had been attempted
HS tank 5	2	Tried, but couldn't test	T: Plumbing problems	Would have had similar problems if testing had been attempted
Mogas	3	T	--	--
Golf course	4	--	--	T

[a] Letter T indicates the tank or tank system was tested.
[b] Dash (--) indicates testing was not conducted.

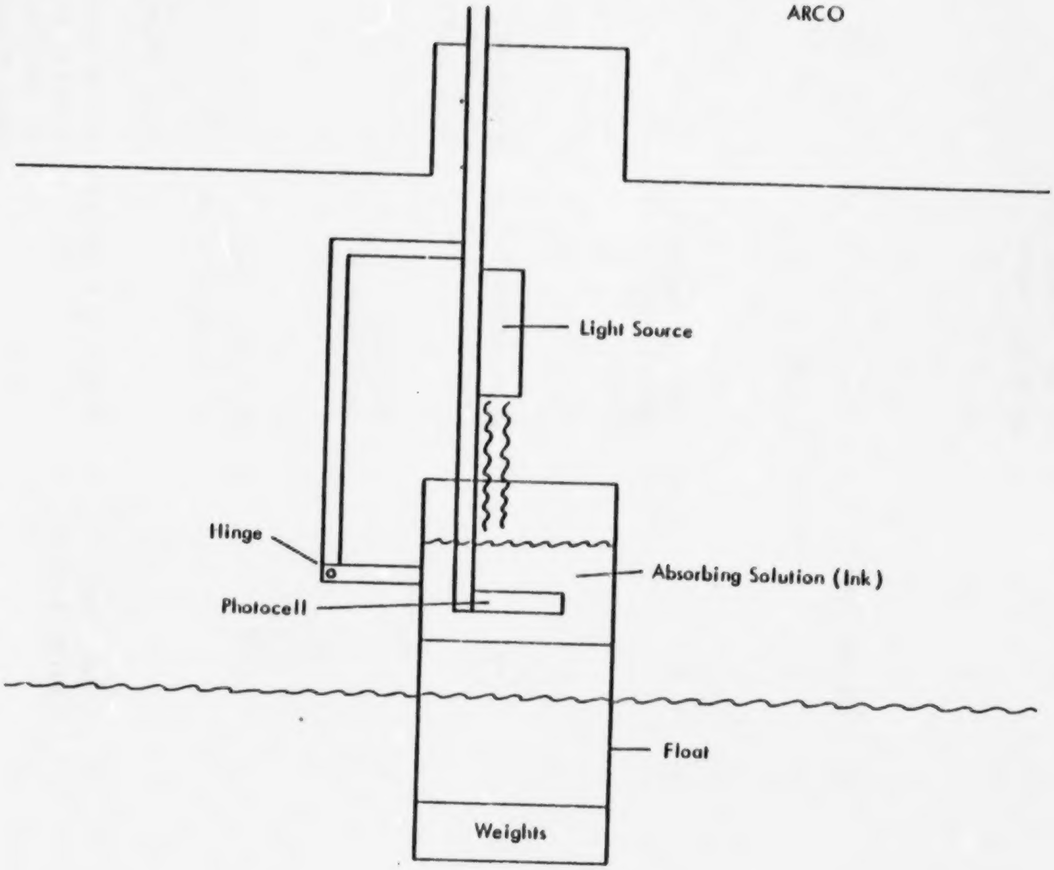


Figure 7. The ARCO test apparatus.

Evaporation effects are minimized by utilizing a spray device to saturate the atmosphere above the surface of the liquid. The method is somewhat sensitive to vibration caused by nearby traffic or wind which may cause a surging effect on the fluid. There is no attempt to compensate for water table effects since it is likely that under actual use conditions this condition would result in the finding of water in the tank. Vapor pockets and end deflection effects are not a problem because the tank is not overfilled.

The entire test can be conducted in 3 to 4 h. Generally, there are few site preparation problems since the test operates under normal operating conditions. Calibration checks are performed at hourly intervals, and testing continues until consistent results are obtained.

2. Leak Lokator Method

The standard operating protocol for Leak Lokator was proprietary. The description provided here is based on observation of the testing done on this program. MRI discussed points of the method with Leak Lokator personnel. Current practice on standard operating procedure may differ from this description.

The Leak Lokator method is based on the buoyancy principle. A schematic of the test equipment is shown in Figure 8. The sensor (a float) is suspended in the fluid from an analytical balance. Any changes in the level of the fluid will produce a change in the buoyancy of the sensor which is detected by the analytical balance. The balance is equipped with an electronic sender which transmits the signal to a strip chart recorder where it is recorded continuously. To quantify the instrument response, a calibration bar of known volume displacement is immersed in the fluid and the effect is noted on the strip chart. This information (chart deflection per volume) is used to convert the level changes produced by the sensor into volumes. The resolution of the device is of the order of 0.001 gal.

The temperature of the fluid is monitored using a thermistor located at the center of the tank. The temperature is monitored continuously on a strip chart and on a digital meter with a resolution of 0.001°F. The readings from the meter are recorded manually on the strip chart at frequent intervals. The meter readings are also used to calculate the temperature correction for the leak detection.

The method can be used to test either the tank or the complete system by adjusting the level of product to above or below the piping. It is assumed that the pressure head of the fluid is sufficient to overcome the masking effect of any water table that may be present. Evaporation effects are compensated for by filling the sensor with the same fluid as is in the tank. Evaporation of fluid from the surface of the liquid in the tank is offset by an equivalent loss from the sensor.

A minimum of 2 h is required to run the test, including setup time, if there are no site preparation problems. In addition, a stabilization period of 8 h after filling is recommended to reduce temperature fluctuations.

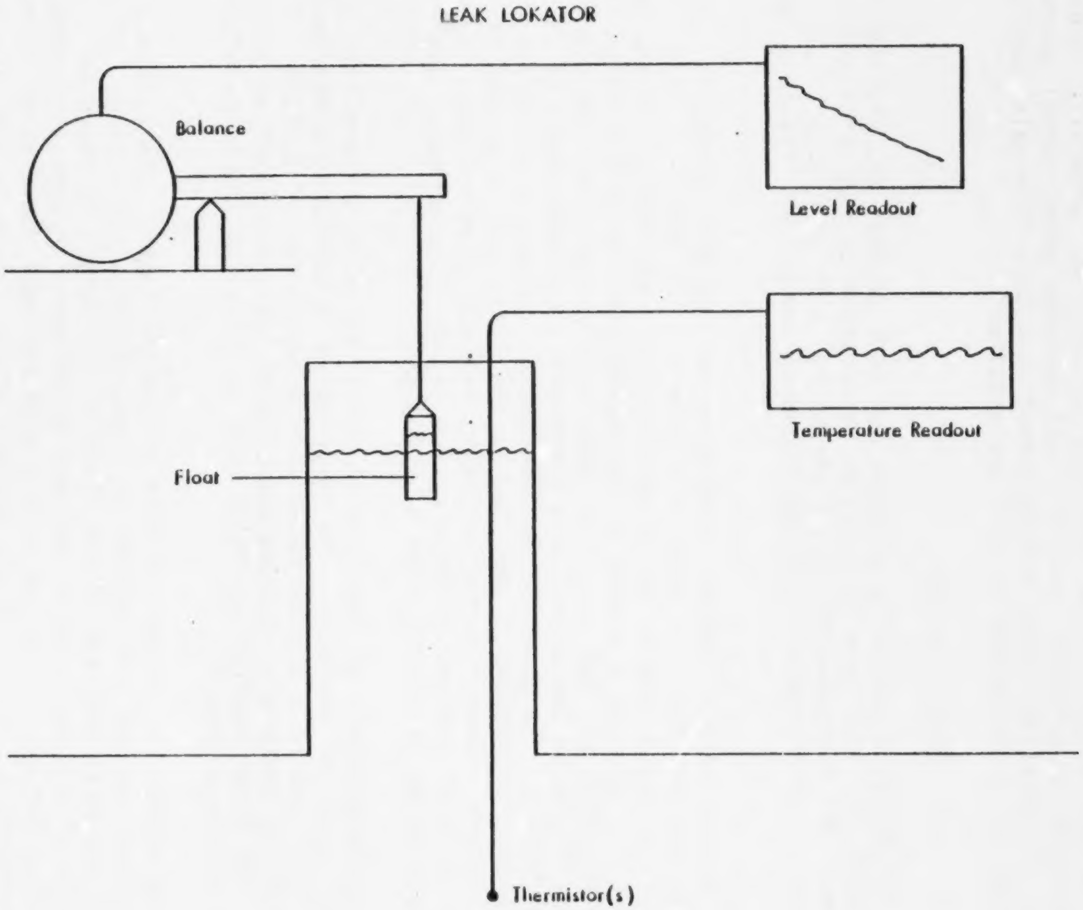


Figure 8. The Leak Lokator test apparatus.

The testing is conducted by monitoring the level change for a period of around 10 min. The temperature is monitored for at least an hour before and after the test. Additional 10 min tests can be conducted if necessary to verify the test results or if the temperature data suggest that it is desirable to do so.

3. Petro-Tite Method

This test is essentially a specialized fluid-static (standpipe) test that provides correction for temperature and water table effects. A schematic of the test apparatus is shown in Figure 9.

The test is conducted by monitoring at regular intervals the fluid level in the standpipe and the temperature of the product in the tank. The fluid in the standpipe is releveled, using a graduated cylinder, to the same reference point following each reading, and the volume added or subtracted from the standpipe is recorded. The observed volume change is then corrected for temperature effects using the coefficient of expansion of the fluid and the temperature change. The corrected volume and time are then used to determine the leak rate.

There are several key features of the Petro-Tite method which should be noted. First, the fluid is stirred prior to and during the test to produce uniform temperature behavior in the tank. A circulating pump draws fluid through a suction tube from at least 6 in. below the tank top. The product is then discharged from a nozzle located near the bottom of the tank but above any water which may be present in the tank. The nozzle is directed upward at an angle of 45 degrees from the center line of the long axis of the tank to produce a swirling motion of the fluid. The temperature is monitored with a thermistor which is located near the inlet to the suction line. If mixing is incomplete, the temperature behavior can be erratic.

Second, the static pressure on the tank is adjusted to account for the effects of any external water table that may be present. The standpipe is always raised to the level calculated to produce a net positive pressure at the bottom of the tank that is 4 lb above the back pressure of the water table. If there are no monitoring wells at the location, a small bore hole is drilled to determine the position of the water table. This process eliminates any masking effects which might be produced by the water table. The higher head pressure also enhances the flow of fluid through any holes which might be present, making leaks easier to detect.

Third, at the beginning of the test, the net pressure in the tank is established at 5 lb to accelerate the outward deflection of the ends of the tank. It is usually possible to determine when the outward deflection is complete by inspection of the "high level" data. After a period of time, depending on the diameter of the tank, the head pressure is lowered to 4 lb. At this point the ends of the tank should stabilize relatively quickly and the remainder of the data is then collected at the "low level."

The temperature resolution of the unit is 0.003°F. The volumes of fluid used to relevel the standpipe are recorded to the nearest 0.005 gal.

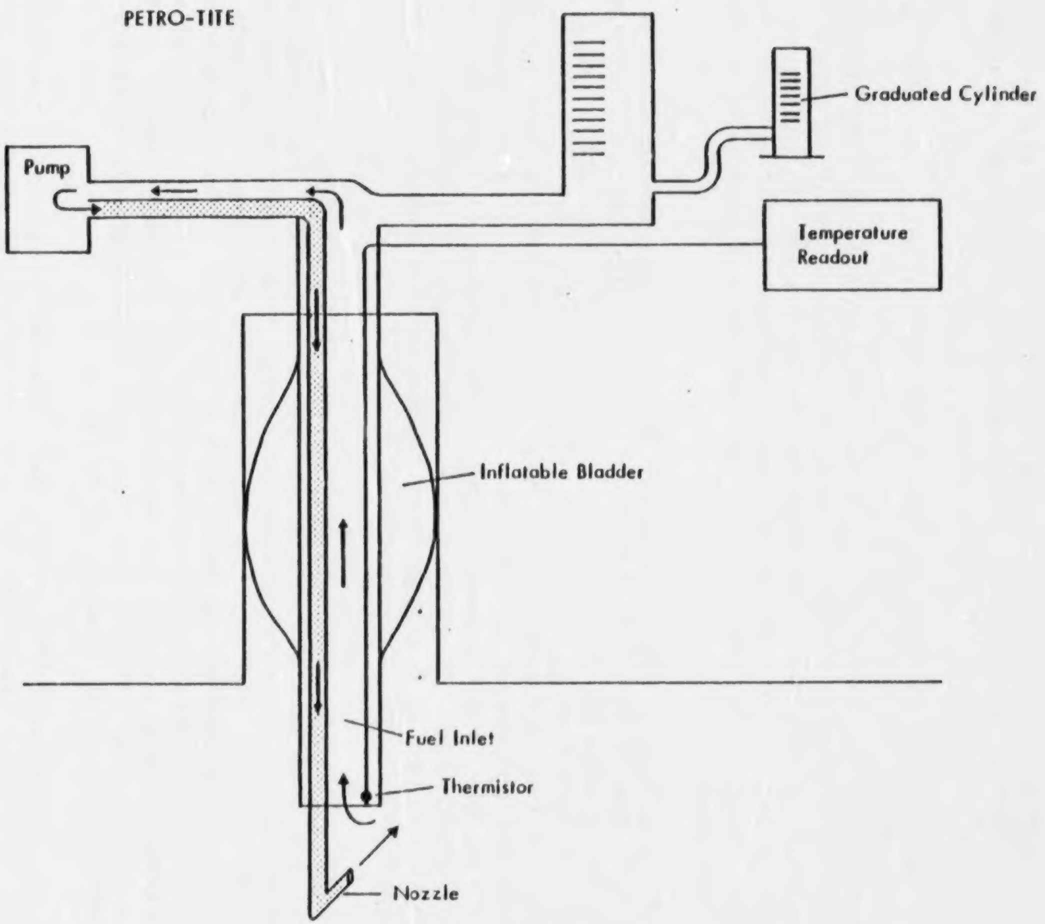


Figure 9. The Petro-Tite test apparatus.

The Petro-Tite method tests the entire system. If a tank-only test is required, the tank must be isolated by disconnecting all the lines leading to the tank. Independent tests of the lines are usually included as a part of the Petro-Tite test if any leaks are detected in the system. The time to conduct the test, including set up, is of the order of 4 h if no site preparation problems are present.

Vapor pockets are said to be detected by the behavior of the fluid level in the standpipe. If any vapor pockets are present, the tank must be excavated and the vapor removed by installing a bleed valve before the test can be completed.

Since the entire system is tested, it is possible that some leaks which are not environmentally significant will be detected. For example, the Petro-Tite method will indicate a large leak for a system with a broken vent pipe line. Since this line does not normally contain product, the leak is not environmentally significant.

The normal test procedure involves the collection of four sets of data at 15-min intervals. The observed volumes are each corrected for temperature, and the net values are summed to obtain the product loss for 1 h. The test can be extended if the results suggest that additional data are needed.

C. Experimental Procedures

1. Field Testing

The design for the development study was as follows. A total of 13 tanks at five facilities were tested. It was originally planned that each tank was to be tested by all three methods. Difficulties in scheduling and plumbing problems at some sites, however, precluded a complete round of testing. The tanks to be tested at each site were chosen on the basis of availability. In addition, facilities in different geographic areas were selected to represent a variety of soil types and other environmental conditions.

The evaluation program included baseline tests and tests under simulated leaks. All tests were conducted separately; i.e., tanks were tested by only one crew at a time. Also, the leak rates simulated were selected in random order and were blind to the test crew. Temperature profiles were usually taken before and after each test by lowering a thermistor into the tank at 6- or 12-in. intervals. These profiles are presented in Appendix D.

a. Standard Baseline Tank Tests

Baseline tests were standard leak detection tests performed by each method without leak simulation. Each organization was asked to perform the test exactly as if it were a routine test to be done on the national survey and inform MRI when it was completed. MRI placed no time or other constraints on this part of the evaluation.

b. Leak Simulation Tests

After the baseline tests were completed by each company, MRI asked that additional testing be done by each firm's test crew under the same conditions but with a simulated leak rate blind to the test crew. The simulated leak was induced using the leak simulation system described in Section III. The crews were again asked to inform MRI when their test was completed under these conditions. In all cases the simulated leak rate was held constant for a period of 1 h or more. After each crew had performed a test to its satisfaction under the simulated leak rate, a second simulated leak at a new rate was induced. A total of four simulated leak rates were used, in random order, one of which was zero, and should have duplicated the conditions of the baseline test. The crews were told neither the simulated leak rates nor exactly when the new rates started. They were told, however, when they should begin testing and were asked to tell MRI when their testing under that condition was complete. The exact simulated leak rates were computed by collecting and weighing the product pumped out of the tank and correcting the mass to the average tank temperature before converting to volume. The average tank temperature was independently measured by MRI by placing a thermistor halfway into the fuel and taking readings every hour on a digital readout.

c. Soil Coring and Analysis

An ancillary activity conducted during the development study evaluations was the collection and analysis of soil cores from one of the facilities. The objective of this effort was to gain some experience and insight into this type of external monitoring. The procedures used and results obtained are described in Appendix F.

2. Data Reduction and Analysis

The data resulting from the testing at the development sites consisted of three data sets: baseline test data, simulated leak data, and time series analysis of the ambient volume fluctuations after the simulated leaks were removed. In some cases, a zero rate was also simulated. In these cases the simulation system's peristaltic pump motor was operated to ensure that the selected rate was blind.

a. Baseline

The baseline data for each method were tabulated and compared for each tank where more than one method was used to test the same tank. Where differing conclusions regarding the tightness of the tank were obtained, the data and conditions of the test were further examined in an effort to resolve the conflict.

The characterization of a tank as tight or leaking was a subjective judgment by MRI based on analysis of all of the test data and by visual observation around the test site. After the testing was completed, the Pitstop South tank was excavated and found to be leaking around the fill pipe flange. Since none of the other tanks were excavated, the judgments were inferred from the extended test data analysis.

b. Leak Simulation Regression

The first analytical approach was to fit a linear regression to the data from each tank and method, regressing reported leak rate on the simulated leak rate using only the data collected during the simulations. Ideally, the slope of this regression should be one. The intercept of this regression represents an estimate of the leak rate of the tank system when there is no simulated leak. The difference between the intercept of the regression line and the test result from the baseline test provides an estimate of bias or accuracy of the test. The variability of the data about the regression line provides an estimate of the precision of the test. Combining these two measures yields an estimate of the mean square associated with the testing method, reported in this document's data tables as RMS (or root mean square error).

In general, the three methods performed similarly. Each had difficulty with some tanks and performed well with others.

c. Description of Ambient Noise Analysis

The second analytical approach was to remove the simulated leaks from the data to produce volume, temperature, and temperature compensated volume-time series that were longer than normally used during a tank test. These data were analyzed to determine whether the results obtained during a standard tank test period (i.e., a baseline test) were consistent with longer test times and to determine whether the temperature induced volume changes adequately accounted for the total volume changes. The data received from ARCO were inadequate for this type of analysis, so ambient noise analysis was performed only on the Petro-Tite and Leak Lokator data.

(1) Petro-Tite Method

Continuous time series data of the change in volume and the change in temperature (converted to volume using the product volume and the coefficient of thermal expansion) were collected for an entire day of Petro-Tite testing. These data were generated from the data collected every 15 min by subtracting the simulated leak volume from the measured volume. The time series included the baseline test data and were 3 to 6 h in duration. The magnitude of the simulated leak was changed in the field during a 15-min sample interval after each 1-h Petro-Tite measurement period. For the continuous time series, the volume change used for this 15-min interval was an average of the volume changes observed before and after this period.

Cumulative time series of volume, temperature, and temperature compensated volume were then generated for analysis. The temperature compensated time series were generated by subtracting the temperature (expressed in volume) from the measured volume on a point-by-point basis. (This is the same method that Petro-Tite uses.) A least squares line was then fit to the entire cumulative temperature compensation time series to estimate the temperature compensated volume rate for comparison with the baseline test results. The standard Petro-Tite method was used to estimate the temperature compensated volume rate for the baseline tests (i.e., sum of the temperature compensated volume computed for four 15-min periods).

(2) Leak Lokator Method

Time series of the cumulative volume and cumulative temperature (converted to volume using the product volume and the coefficient of thermal expansion) were generated for each simulated leak sequence of the Leak Lokator data. Each time series ranged from a total of 40 min to over 100 min and included four to nine of the standard Leak Lokator volume rate measurement periods. The individual Leak Lokator tests were typically 10 min but ranged from 6 to 18 min. Long time series were not generated because of a gap of 3 to 4 min in the collection of Leak Lokator data between simulated leak sequences. The simulated leak rate was subtracted from the uncompensated volume rate measurements made by Leak Lokator and was converted to volume using the reported measurement time. These volume measurements were then summed to obtain the cumulative volume time series. The mean volume rate for each simulated leak sequence was estimated from the reported Leak Lokator volume rate data. The mean and standard deviation were weighted to produce values equivalent to a 10-min test period. Because most test periods were close to 10 min, similar values of the mean and standard deviation would be obtained without weighting the data.

A continuous time series of temperature was generated from annotated readings of temperature made every 5 to 10 min and placed on the strip chart of temperature by Leak Lokator personnel. Those sections of the temperature-time series which bracketed the volume data for each simulated leak sequence were used to compensate for temperature. Except for the three simulated test sequences which were longer than 1 h, the temperature time series were generally 1 h. The temperature data were converted to a volume time series, and a least squares line was fit to the data to estimate the average rate of change of volume caused by the rate of change of temperature over an hour.

Leak Lokator regarded its standard operating procedures as proprietary. In a standard test of the Leak Lokator, as performed by MRI, the rate of change of temperature was estimated from only two points separated by an hour. A mean temperature compensated volume rate was then computed for each simulated leak period by subtracting the mean rate of change of temperature from the mean rate of change of volume and compared to the results from the baseline test and the other simulated leak test sequences.

D. Results

1. Tank Temperature Conditions

Tank temperature conditions could not be controlled during the tests. The Petro-Tite and Leak Lokator test methods were used to test tanks under different conditions. Whenever possible, MRI made temperature profiles with a single thermistor accurate to 0.01°F in 6-in. depth increments before and after each day of tank testing. In general, a wide variety of different temperature conditions were encountered for each method. Figures 10 and 11 show single temperature profiles made before and/or after some of the Petro-Tite and Leak Lokator tests. The approximate location of the Petro-Tite and Leak Lokator thermistors are indicated. The product temperature conditions are summarized in Tables 10 and 11.

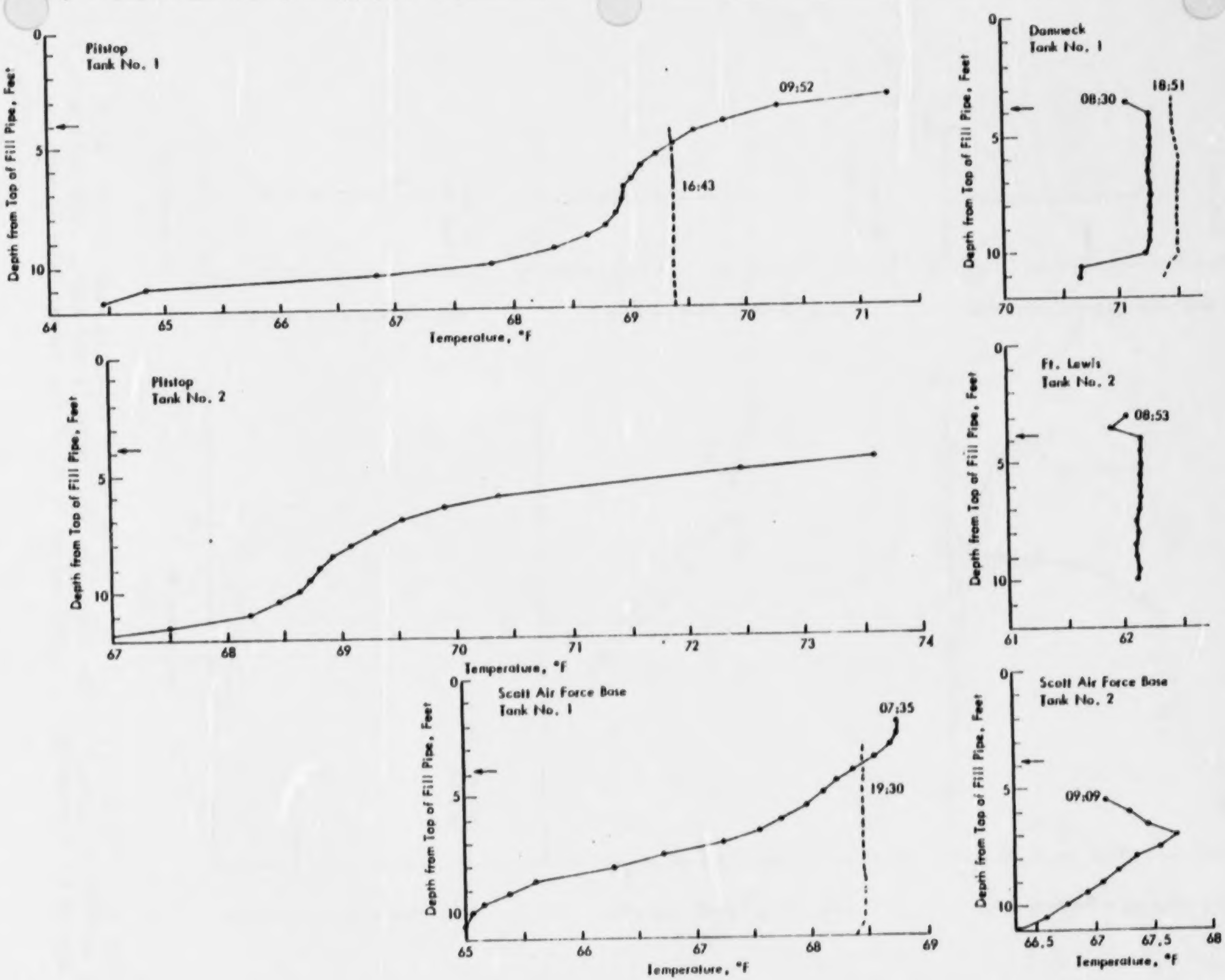


Figure 10. Temperature profiles obtained before (solid) and after (dashed) selected Petro-Tite tests. The maximum distance from the top of the fill pipe is the approximate bottom of the tank. The arrow indicates the location of the temperature sensor.

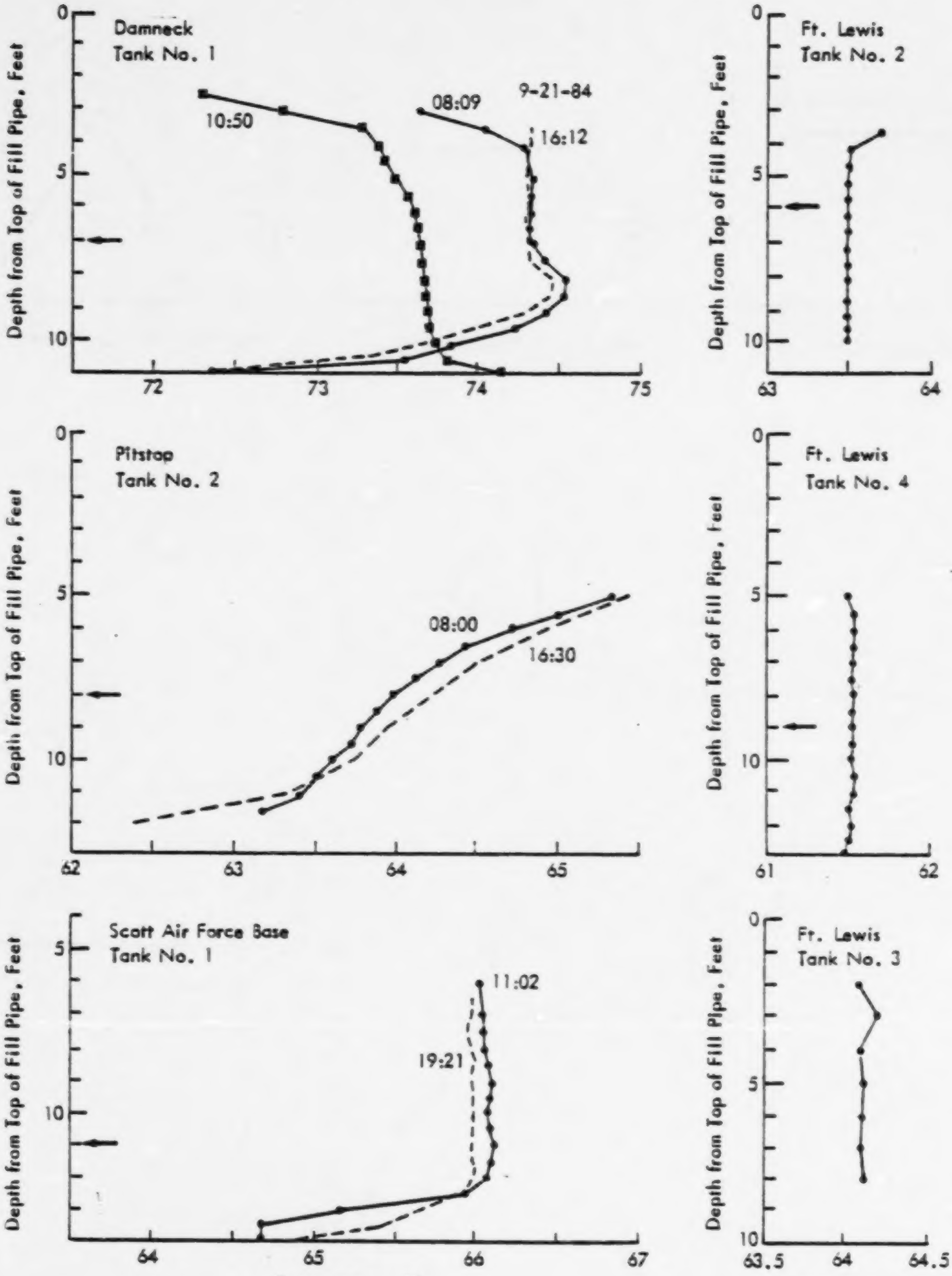


Figure 11. Temperature profiles obtained before selected Leak Lokator tests. The maximum distance from the top of the fill pipe is the approximate bottom of the tank. The arrow indicates the position of the temperature sensor.

Table 10. Petro-Tite Tank Test Temperature Conditions

Location	Tank	Date	Capacity (gal)	Coefficient expansion (1°F)	T Mid-depth (°F)	dT/dz Mid-depth (°F/ft)	Max ΔT (°F)	No. of layers	Stability
Damneck	1	10/4/84	5,072	0.00062425	71.26	~ 0	0.6	2	Stable
Fort Lewis	2 (8C25 rear)	10/9/85	11,860	0.00058875	62.12	~ 0	0.4	1	Stable
Fort Lewis	4 (10E10)	10/11/84	11,914	0.00059088	-	-	-	-	No profile
Pitstop	1 (south)	9/13/84	11,899	0.00063561	68.93	0.08	> 8	3	Stable
Pitstop	2 (north)	9/14/84	7,904	0.00063561	69.08	0.39	> 5	3	Stable
Scott AFB	1 (17)	9/19/84	5,086	0.00063277	67.24	0.84	3.8	3	Stable
Scott AFB	2 (18)	9/18/84	5,086	0.00045130	68.67	-0.03, +0.11	1.4	2	Unstable

Note: The coefficient of thermal expansion was estimated by O. H. Materials. The temperature conditions are approximate and were obtained from individual temperature profiles before the tank tests. A stable temperature profile suggests that temperature decreases monotonically with data.

Table 11. Leak Lokator Tank Test Temperature Conditions

Location	Tank	Date	Capacity (gal)	Coefficient expansion (1°F)	T Mid-depth (°F)	dT/dz Mid-depth (°F/ft)	Max ΔT (°F)	No. of layers	Stability
Damneck	1	9/20/84	5,084	0.0006926	73.65	-0.03	∼ 2	2	Unstable
Damneck	1	9/21/84	5,084	0.0006954	73.35	∼ 0	2.15	2	Unstable
Fort Lewis	2 (8C25)	10/3/84	12,034	0.0006562	63.46	∼ 0	∼ 0.2	1	Stable
Fort Lewis	3 (4194)	10/4/84	12,034	0.0004732	64.11	∼ 0	0.1	1	Stable
Fort Lewis	4 (10E10)	10/5/84	12,034	0.0006653	61.32	∼ 0	< 0.1	1	Stable
Pitstop	2 (north)	10/8/84	8,022	0.0007052	63.98	- 0.25	2.95	1	Stable
Scott AFB	1 (17)	10/11/84	5,076	0.0007028	66.08	∼ 0	1.39	2	Stable
Scott AFB	2 (18)	10/12/84	5,076	0.0007035	66.08	-0.40	1.75	3	Stable

Note: The coefficient of thermal expansion was estimated by Leak Lokator. The temperature conditions are approximate and were obtained from individual temperature profiles before the tank tests. A stable temperature profile suggests that temperature decreases monotonically with data.

Several observations can be made. First, the profile made after the Petro-Tite tests indicates that the circulation produces an isothermal profile to within ± 0.01°F (i.e., the accuracy of the thermistor used to measure the profile) regardless of the initial profile. Whether the temperature is also uniform at other points in the tank is not directly known, but if the temperature were not uniform throughout the tank, large errors in the temperature compensation would be observed. Since large errors in temperature compensation are not observed, we infer that the circulation approach succeeded in producing a uniform temperature throughout the tank.

Second, the Leak Lokator one-thermistor compensation approach should work best for temperature profiles with uniform temperature changes as a function of depth (e.g., Fort Lewis Tank Nos. 2 to 4 and Pitstop Tank No. 2) but would not work well for nonuniform profile changes (e.g., Damneck, Scott AFB Tank No. 1).

Third, the Petro-Tite thermistor, located approximately 45-in. below the top of the fill-tube, may not always extend into the tank sufficiently to avoid temperature fluctuations in the fill-tube and near the top of the tank which are not representative of the tank as a whole. More investigation of the effect of the inlet location is needed.

A summary of the baseline test results for all three test methods is given in Table 12. Data from all development study tests are contained in Appendix H.

It should be pointed out that, because the tanks were tested at different times by different methods, the conclusions reached by each method could be correct only for the times at which the tanks were tested. This could occur if either the environmental conditions changed significantly or if the tank developed a leak after the initial test. It should be noted that the MRI conclusions are based on the results of all the methods used to test each tank system, together with any other evidence, such as product observed in soil or water in the area. In addition, each test company expresses its test results as follows: certified as having passed the test, which means that the measured leak rate is less than the NFPA criterion; or noncertified as having failed the test, which means that the measured leak rate is greater than the NFPA criterion or that excessive noise or product loss results in an inconclusive result. MRI expressed its conclusions about these test results as either tight (certified), leaking (noncertified), or inconclusive (noncertified).

The final conclusion, nonleaking or leaking, was determined by MRI after data analysis. To confirm the results, excavation would have been useful, but this was not possible because all tanks tested were in use.

Table 12. Summary of Baseline Results and Tank Tests Attempted

Facility and tank	ARCO (gal/h)	Leak Lokator (gal/h)	Petro-Tite (gal/h)	MRI conclusion
Damneck	+0.02 C[a]	-0.077 N[b]	+0.003 C	Tight
Pitstop				
1 (south)	+0.02[c] C	-0.741 N (Poor sensitivity)	-2.892 N	Leak
2 (north)	0.0 C	-0.012 C	-0.05 C	Tight
Scott				
1 (17)	Out of time	-0.299 N	+0.004 C	Tight
2 (18)	+0.02[c]	-0.178 N Problem, possibly manifolded	-0.812 N	Leak
Fort Lewis				
1 (8C25 north)	-0.04 C	Leak about gasket-could not test	--	Tight
2 (8C25 south)	0.0[a] C	-0.027 C	-0.342 N	Leak
3 (4194)	--	-0.172 N (Poor sensitivity)	-3.0 N	Leak
4 (10E10)	--	-0.191[d] N	-0.024 C	Leak
Langley				
1 (HS tank 3)	--	-0.448 N	--	Leak
2 (HS tank 5)	Physical problem with tank	-3.0[d] N	--	Leak
3 (MoGas)	-0.03 C	--	--	Tight
4 (Golf course)	--	--	-2.540 N	Leak

[a] Certifiable according to NFPA 329.
[b] Noncertifiable by NFPA standards.
[c] Test OK, but leak (possibly in upper part or piping) not found.
[d] Test appeared OK, but data are inconsistent.
Negative values indicate leak out of tank.
-- indicates testing was not conducted at that tank by the test company indicated.

2. Baseline Tests

a. ARCO Method

Several interesting observations can be made from these data. First, none of the tanks were found by ARCO to be leaking. The ARCO result disagreed with the MRI conclusion for three tanks. It must be noted that the ARCO system tested tanks approximately 75% full and under no additional head pressure. Thus, the ARCO system provides a test more representative of the usual operating conditions of the tank. However, the ARCO system will not detect a leak in or near the top or in the fill pipe, or if there is a leak in the lines. While it may be unlikely that all of the leaks encountered during the study are in the top of the tank, it is a possible explanation. In fact, one of the tanks (Pitstop South) was excavated and found to have a leak in the fill pipe flange at the top of the tank. In a second case (Scott No. 18), the results of all the tests were in question due to anomalous behavior observed by Leak Lokator.

It should also be noted that ARCO's testing in general has determined the percentage of leakers to be approximately 5% in their own systems (Collins 1985). This estimate is considerably lower than was determined in the national survey but is consistent with the differences between the ARCO method and the Petro-Tite method. The ARCO estimate of leakers is also based on tanks that are tested periodically on a regular basis and for which regular maintenance is conducted. It may well be correct for this population of tanks.

b. Leak Lokator Method

The results reported by Leak Lokator disagree with the conclusions reached by MRI on 4 out of 10 tests. The MRI conclusions are based on an extended analysis of all the data, including the data collected by Leak Lokator. In three cases the tank was reported to be leaking when the MRI conclusion was that it was tight; and in one case the tank was reported to be tight when the MRI conclusion was that a leak was present.

Several factors should be noted in making these comparisons. First, extended analysis of the Leak Lokator data (discussed in subsection 4 below, Ambient Noise Analysis) indicates that the primary reason for the differences is probably in the temperature compensation approach used by Leak Lokator.

Second, MRI's conclusions are based in part on the Petro-Tite data as well as the Leak Lokator results. There is no reason to believe that the condition of the tank was different from test-to-test, but this remains a possibility.

Third, since the Leak Lokator tests are generally conducted with the product level below grade, leaks which are in the piping above the product level will not be detected. This could have been the situation at the Fort Lewis Tank No. 2. If this situation existed, the results reported by Leak Lokator would be correct for the tank, but incorrect for the complete system.

A large leak in the Scott Tank No. 1 was reported by Leak Lokator whereas the tank was found by Petro-Tite to be tight. The conflicting conclusion is difficult to reconcile because interactive effects between Tanks 1 and 2 were observed during the testing of Tank No. 2 by Leak Lokator. This could be explained if the tanks were manifolded together. However, if this were the case, it is expected that a much larger leak would have been observed during the Petro-Tite test. In addition, since the tanks are parallel to each other, interactive end effects which are sometimes observed when tanks are placed end-to-end seem unlikely. The reasons for the inconsistencies at Scott are not apparent from either observations of the crews or the data.

The reported results at Damneck indicated a small system leak. An additional test at product level below the piping indicated the tank to be tight. Extended analysis of the data indicates that temperature effects, not accounted for by the Leak Lokator temperature compensation procedure, could account for these differences.

c. Petro-Tite Method

The Petro-Tite test results agreed with the MRI conclusion in all nine systems tested. In one instance, Pitstop Tank No. 2, extended analysis indicated volume increases were actually occurring which would have invalidated this test (due to a volume increase greater than could be accounted for by temperature effects, by more than +0.05 gal/h) if baseline data had been taken 1 to 2 h later (discussed in subsection 4 below, Ambient Noise Analysis).

Since this method applies a significantly higher head pressure, always tests the entire system, and always accounts for water table effects, it would be expected to report larger leaks with a higher frequency than other methods. Where testing of leaking tanks overlaps with other methods, the prediction of higher leak rates seems to be the case with Petro-Tite (Pitstop No. 1, Scott No. 2, and Fort Lewis Nos. 2 and 3). However, the frequency of reporting leaks is lower than that for Leak Lokator. Of eight overlapping tests with Leak Lokator, Petro-Tite reports four leaks while Leak Lokator reports six. Of five overlapping tests with ARCO, Petro-Tite reports three leaks while ARCO reports none.

3. Leak Simulation Results

a. ARCO Method

The ARCO method was used to test seven tanks. Of these, on one tank, only the standard baseline test was run; no simulated leak tests were run because the standard test required all of the time available. Another test produced only two data points, the baseline test and one simulated leak rate. The other five tests had the baseline leak rate and several simulated leak rate tests. However, in most cases, only five or six data points were available.

The results from the leak simulation tests using the ARCO method are summarized in Table 13. Sample data are shown in Table 14 and Figure 12. This method reported none of the tanks to be leaking. However, other methods gave different results for some tanks. The conclusions about the condition of the tanks are summarized in Table 12. The ARCO result disagreed with the conclusion for three tanks, namely, Pitstop South, Scott Tank 18, and Fort Lewis Tank 8C25 South. However, it should be noted that the ARCO system tested tanks at approximately 75% full. Thus, the ARCO system may provide results more representative of the usual operating conditions of the tank. However, the ARCO method would not detect a hole in or near the top, in the fill pipe, or a leak in the lines. Hence, the reporting of no leaks by ARCO is not necessarily inconsistent with the fact that other test methods reported leaks in the same systems. In fact, the Pitstop South tank was excavated and found to have a leak at the fill pipe flange.

The data in Table 12 indicate that the ARCO test method performed without difficulty at the Damneck, Pitstop North, and Fort Lewis 8C25 South test facilities. If an apparent outlier is removed from the data, the method also performed well at the Langley facility. One of the sites (Scott Tank 18) showed no apparent trend between the reported leak rates and the simulated leak rates. One other test, at Fort Lewis, gave a slope substantially different from one.

These results indicate that the ARCO method can give a precise determination of a leak rate under some operating conditions. It is limited to detecting leaks in the lower 75% of the tank. It can detect inflow or outflow, but would be defeated if the water table were at a level that approximately balances the hydrostatic pressure of the product. It is also subject to interference from wind and is sensitive to vibration. It has the advantage of not requiring an overfilled tank, but this is counterbalanced by the disadvantage of not being able to detect potential leaks in the upper quarter of the tank. The test relies on a very sensitive level monitor to detect changes in the level of the product, so it can be disturbed by vibration of or disturbances in the liquid level in the tank. It is self-compensating for temperature.

b. Leak Lokator Method

The Leak Lokator method was used to test 10 tanks. Of these, two tanks had only baseline tests and no simulated leak tests conducted. The Leak Lokator test conclusions agreed with MRI's conclusion in 6 of the 10 tank tests. Of the other four, the Leak Lokator test did not certify three tanks that were determined to be tight and did certify one tank that was determined to be leaking.

A summary of the results from the leak simulation tests using the Leak Lokator method is presented in Table 15. Sample results are shown in Table 16 and Figure 13. The leak rates were reported by Leak Lokator over approximately a 10-min period. Several leak rates were determined during each simulated leak period. These rates were regressed on the simulated leak rates. Table 12 lists each tank and its baseline leak rate reported by Leak Lokator before any simulated leak tests were run.

Table 13. Results of Leak Simulation Tests Using ARCO Method[a]

Tank	Baseline rate (gal/h)	Intercept (gal/h)	Bias (gal/h)	Slope	SE (gal/h)	RMS (gal/h)
Damneck	0.02	-0.023	-0.003	1.049	0.022	0.023
Pitstop south	0.02	-	-	-	-	-
north	0.0	-0.092	-0.092	0.809	0.041	0.101
Scott 18	0.02	-0.145	-0.165	-0.044	0.099	0.192
Fort Lewis						
8C25 south[b]	0.0	-0.005	-0.005	1.140	-	-
8C25 north	-0.04	-0.094	-0.054	0.493	0.047	0.072
Langley						
MoGas	-0.03	-0.336	-0.306	0.419	0.367	0.478
	-0.03[c]	-0.027	0.003	1.167	0.118	0.118

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[a] Negative = leak out; positive = leak in; bias = intercept - base.

[b] Two points only.

[c] Outlier removed.

Table 14. Sample of Simulated Leak Data for ARCO Test at Damneck

Test	Rate (gal/h)	SIM rate (gal/h)	Base rate (gal/h)
ARCODN.SAS; 1 Damneck m = 1.12, y' = 0.01	-0.110	-0.075	-0.035
	-0.370	-0.319	-0.051
	-0.030	0.000	-0.030
	+0.020	0.000	+0.020
	-0.170	-0.166	-0.005
		Mean =	-0.020
		Std Dev =	0.025

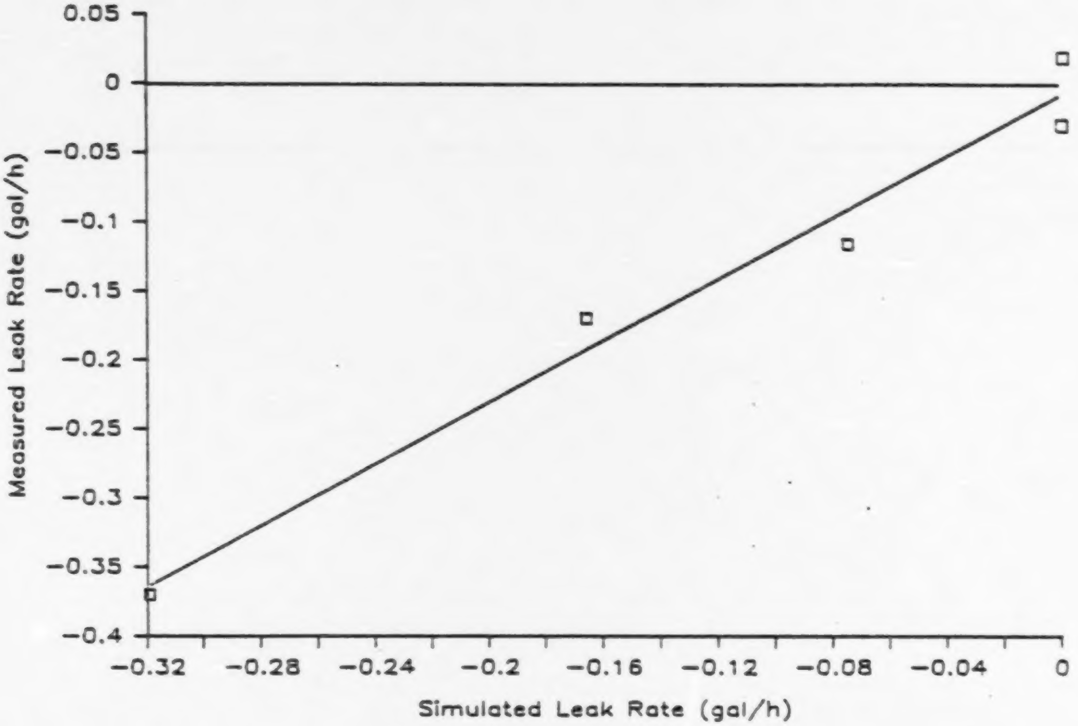

Figure 12. Simulated leak data for ARCO test at Damneck.

Table 15. Results of Leak Simulation Tests Using Leak Lokator Method[a]

Tank	Baseline rate (gal/h)	Intercept (gal/h)	Bias (gal/h)	Slope	SE (gal/h)	RMS (gal/h)
Damneck (@ 120")	+0.0775 @ 125 (+0.008 @ 118)	-0.0825 (-0.005)	-0.005 (-0.13)	0.786	0.025	0.0255 (0.028)
Pitstop south	-0.524	-	-	-	0.209	-
north	-0.012	-0.026	-0.014	0.879	0.015	0.021
Scott 17	-0.299	-0.366	-0.067	0.839	0.048	0.082
18	-0.178	-	-	-	0.047	-
Fort Lewis						
8C25 south	-0.027	-0.010	0.017	0.734	0.097	0.099
4194	-0.171	-0.159	0.013	0.749	0.026	0.029
10E10 NTC[b]	-0.191	-0.596	0.405	0.541	0.165	0.437
TC[c]	-0.191	0.069	0.260	0.835	0.098	0.278
Langley						
HS 3	-0.448	-0.641	-0.193	-1.78	0.048	0.199
HS 5	-3 or more	0.126	0.126	2.43	0.304	0.329

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[a] Negative = leak out; positive = leak in; bias = intercept of their (adjusted for base) regression; intercept = bias plus base.

[b] NTC - not temperature corrected.

[c] TC - temperature corrected by Leak Lokator.

Table 16. Sample of Simulated Data for Leak Lokator Test at Pitstop North

Test	Rate (gal/h)	SIM rate (gal/h)	Base rate (gal/h)
LOKLEAK.SAS; 4	-0.289	-0.351	+0.062
Pitstop north	-0.283	-0.351	+0.068
m = 0.882, y' = 0.012	-0.285	-0.351	+0.066
	-0.297	-0.351	+0.054
	-0.294	-0.351	+0.057
	-0.258	-0.351	+0.093
	-0.289	-0.351	+0.062
	-0.068	-0.098	+0.030
	-0.072	-0.098	+0.026
	-0.080	-0.098	+0.018
	-0.077	-0.098	+0.021
	-0.209	-0.224	+0.015
	-0.188	-0.224	+0.036
	-0.198	-0.224	+0.026
	-0.209	-0.224	+0.015
	-0.201	-0.224	+0.023
	-0.197	-0.224	+0.027
	+0.028	0.000	-0.028
	+0.027	0.000	-0.027
	+0.022	0.000	-0.022
	+0.018	0.000	-0.018
		Mean =	-0.038
		Std Dev =	0.022

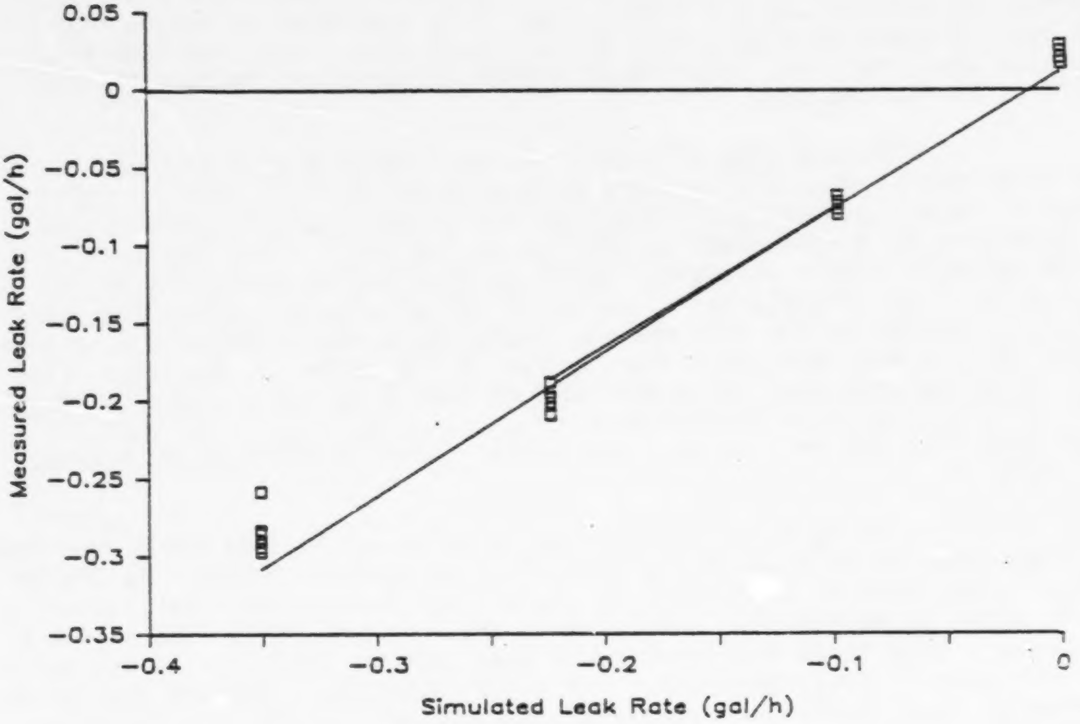

Figure 13. Simulated leak rate data for Leak Lokator test at Pitstop North.

The RMS errors for the Leak Lokator simulated leak results ranged from about 0.02 gal/h to 0.44 gal/h. The standard errors ranged from 0.015 to 0.304. Among the tanks judged to be tight, the standard errors ranged from 0.015 to 0.165 and the RMS error ranged from 0.021 to 0.437. The large values for the upper end of the range are from a test that MRI's analysis suggests was not valid. No indication of questionable results was received from Leak Lokator. If that data point is excluded, the upper ends of the ranges become 0.048 and 0.082. These error estimates refer to the leak rates as reported by Leak Lokator. With the ability of Leak Lokator to obtain multiple leak rate determinations fairly rapidly (about one every 10 to 15 min), one could presumably reduce these error estimates by making several leak rate determinations at a tank and averaging them. Provided that the estimates are consistent, this should reduce the error and improve the precision of the test method.

The Leak Lokator method records a level measurement determined by a float and an analytical balance on a strip chart. The chart is calibrated by rapidly inserting and removing a calibration bar of known volume and observing the displacement of the line on the chart. The leak rate is determined by fitting a straight line visually to the strip chart tracing, reading its slope in divisions of the chart per minute, and converting this to a volume change by the calibration. Temperature compensations can be made on the basis of a single thermistor located at the center of the tank. (The Leak Lokator manufacturer has stated that it uses three thermistors in large tanks, but its test crew did not do so in any of these tests. In most of these tests they did not use any temperature compensation in estimating the leak rates.)

Fitting the straight lines visually and reading the slopes from them introduces an observer factor into the leak rate estimation. In the absence of other data on inter-observer variability, MRI had an investigator with a degree in mathematics independently draw the slope lines and estimate the slopes. Only those data selected by Leak Lokator for leak rate estimation were used in this comparison. The values obtained by MRI and the values reported by Leak Lokator were compared. The estimate of the inter-observer variability was 0.04 gal/h. While this represents only limited information on inter-observer variability, and while that variability might be smaller for trained personnel experienced in the method, it is large enough to cause concern relative to the desired criterion of 0.05 gal/h. A substantial improvement in the method would seem to be to convert the strip chart data to digital form so that a slope could be estimated mathematically--say, by least squares--to remove this source of possible variability.

Additional analyses were performed on the raw Leak Lokator data. While the data do not provide a continuous or exactly periodic measurement of volume changes, they nearly do so when there are no problems. Gaps occur when the strip chart scale is reset and when the balance used to monitor the buoyancy of the level sensor is adjusted back to scale. This would typically be about a minute on each end of a 10- to 12-min level measurement. Thus, time series analyses can be used to shed additional light on the performance of the method.

A comparison of the leak rates measured by Leak Lokator and the simulated leak rates for the test at Pittston North is displayed in Figure 14. The differences between the simulated rates and those reported by Leak Lokator are plotted over time in Figure 15. The fact that the data are not equally spaced reflects that the determinations of slopes were based on slightly different time intervals. Also, gaps of somewhat different lengths occurred as the scale was reset.

The leak rates reported were weighted by the times, interpolating linearly through the gaps, and summed to give a cumulative volume change. This is plotted in Figure 16. Since this is based on the leak rates reported by Leak Lokator, it should represent that method's temperature compensated leak rate determination. Leak Lokator's temperature compensation appeared to be based on two points an hour apart. Also plotted in the figure is a cumulative volume change that one would expect from thermal expansion (contraction) from the temperature changes as noted on the strip chart. It should be noted that substantial differences could occur depending on which two points are used for temperature.

Use of a smoothing technique for the temperature data, followed by use of the smoothed temperature data for temperature compensation might result in smaller variability of the Leak Lokator method. This would necessitate use of a fairly large number of individual leak rate estimates over a period of 2 h or more. It would also be desirable to keep the data gaps as small as possible, as large gaps would complicate and possibly invalidate this type of analysis. Simple use of several leak rate determinations averaged would reduce the standard error. Alternative methods of temperature compensation might improve the precision and accuracy of the method as well.

The variability of a single leak rate measurement tends to be somewhat large relative to a 0.05 gal/h criterion, but the ability of the system to obtain leak rate determinations in about 10 min once the test is running would allow multiple determinations and averaging to reduce this variability. The method has the advantage that its level monitoring system can be used at any desired level (head pressure). Thus, if line leaks are a problem, the testing could, in principle, be done below the level of such leaks. If such testing is done inside the tank rather than in the fill pipe, sensitivity is greatly reduced because much smaller level changes would be produced by a leak of a given size.

In addition, hydrostatic pressure from the water table could pose a problem for this test. No check on water table was made. While the ability of the method to test at different levels is an advantage, it can also present difficulties. Testing did not appear to be standardized to any specific level. Since the leak rate through a given aperture would change with head pressure, testing different tanks at different levels makes leak rate determinations difficult to compare and quantify.

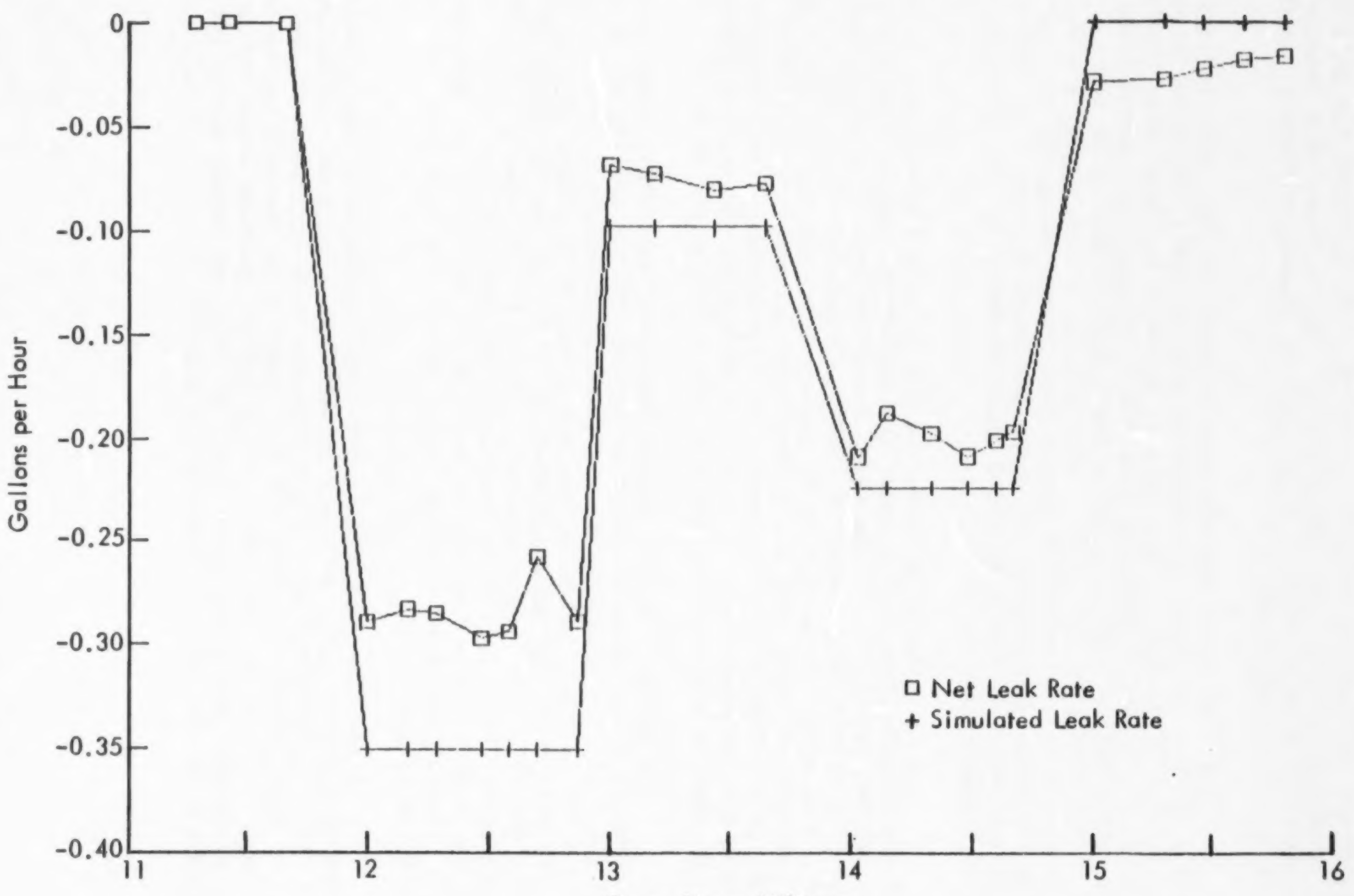

Figure 14. Net leak rate and simulated leak rate for Leak Lokator test at Pitstop North.

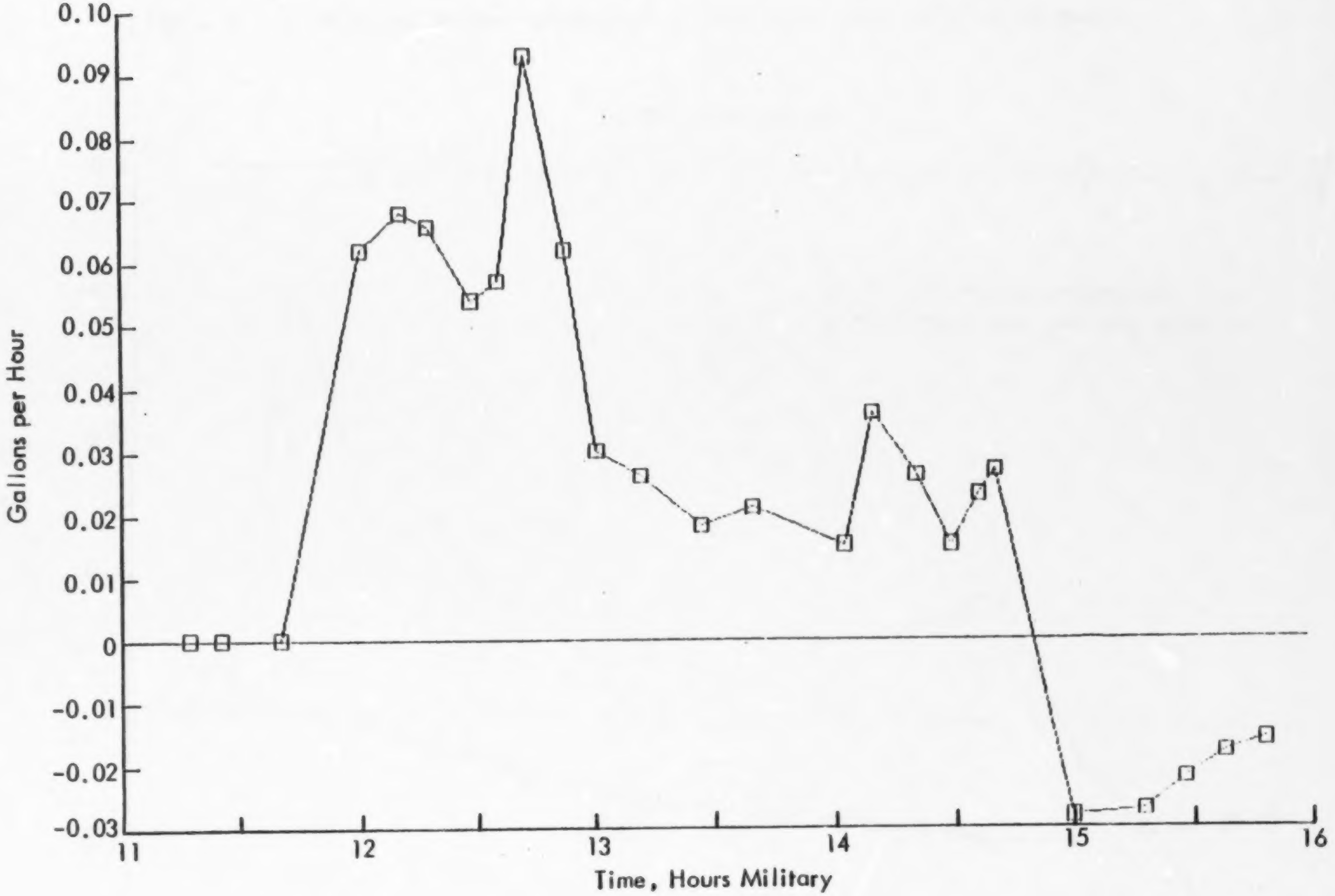

Figure 15. Net leak rate minus simulated leak rate for Leak Lokator test at Pitstop North.

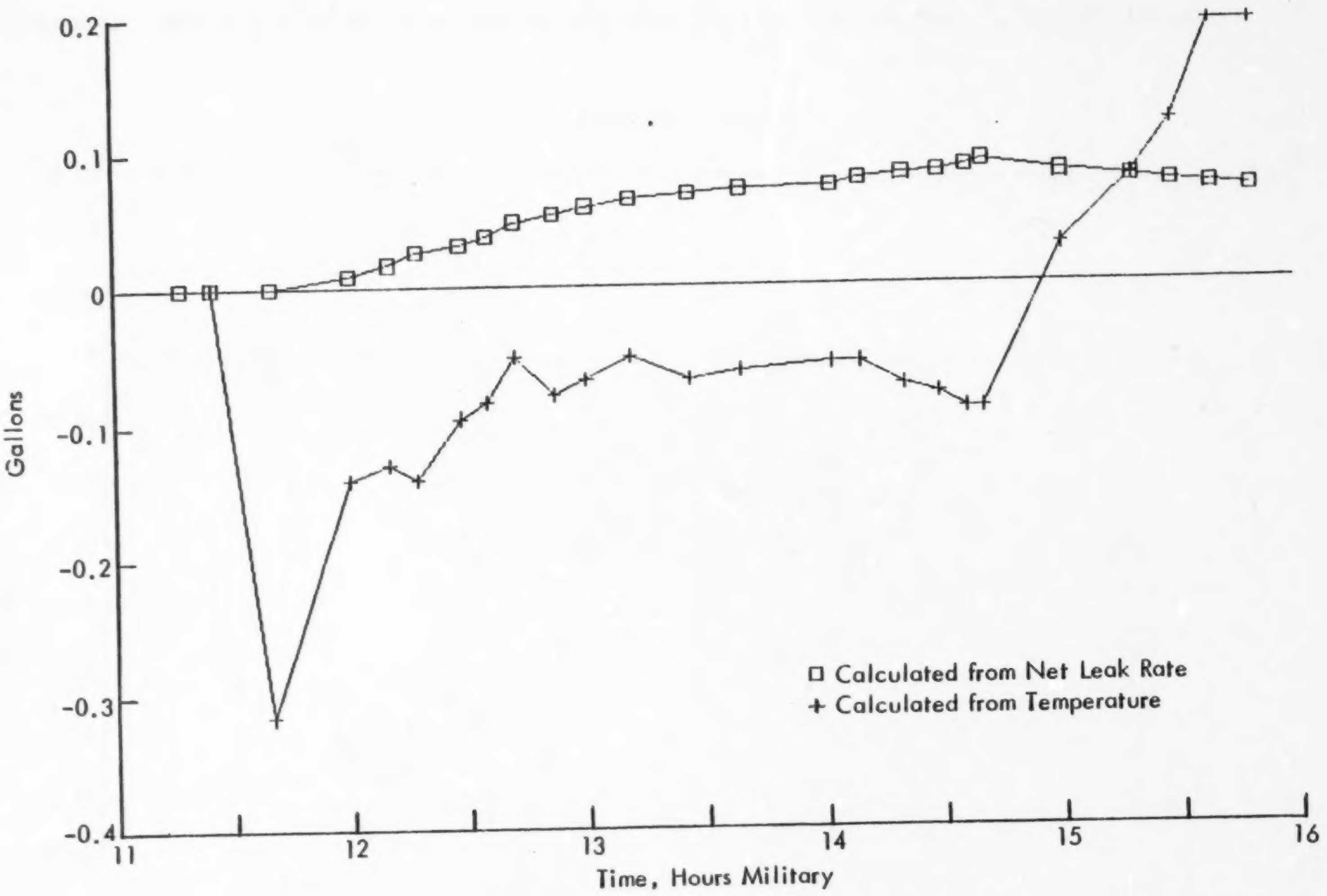

Figure 16. Cumulative volume change for Leak Lokator test at Pitstop North.

c. Petro-Tite Method

The Petro-Tite method was used to test nine tanks during the development study. Four of the systems tested had leak rates so large that simulation of additional leak rates on the order of 0.2 gal/h was not feasible. Simulated leak rate testing was performed on five tank systems. On these systems the analysis of the simulated leak rate data was done, regressing the measured leak rates on the simulated leak rates. Additional data analysis, utilizing cumulative volume changes, after subtracting simulated leak rates, was also done on these data sets.

The standard point-to-point temperature compensation consists of measuring the temperature change, converting it to a volume expansion or contraction by multiplying by the thermal coefficient of expansion and the volume of the tank, and then for each point subtracting this change from the measured volume change.

A summary of the results from the leak simulation tests using the Petro-Tite method is presented in Table 17. Sample data are shown in Table 18 and Figure 17.

The Petro-Tite test results agreed with the MRI conclusions about the presence of a leak for all tank systems tested except one. On this test field observation documented a leak in a manway gasket that began after Petro-Tite had finished the standard test. The method was also able to perform a test of all tank systems for which testing was attempted. However, in some cases, substantial line leaks were found, indicating a system leak that would have to be repaired or isolated before a separate test on the tank could be done.

For two tank test sites with large estimated leaks (Fort Lewis 8C25 South and Pitstop South) it was possible to make a separate estimate of the standard error of the leak rate even though no simulated leak testing was done. This was possible because the Petro-Tite method made several independent measurements of the leak rate over 15-min intervals. The variation among these 15-min rates yields an estimated standard error.

The root mean square errors for the Petro-Tite results ranged from 0.036 to 0.193 for tanks judged to be tight. The 0.193 is rather large. That tank posed special problems. Its analysis was discussed in more detail, leading to the conclusion that the 0.193 is not representative. Error estimates on tanks judged to be leaking were larger, ranging up to 0.24 gal/h. Larger errors are to be expected for systems with large leaks because large leaks make it difficult to maintain product level and so therefore to obtain an accurate volume. However, the errors remained acceptably low relative to the associated leak rates. It should be noted that these error measurements represent an estimated error for a single determination of the volume change rate. The Petro-Tite test uses an average of several determinations, so the effective error is the standard error rather than the standard deviation. The standard error is calculated by dividing the standard deviation by the square root of the number of rates averaged.

Table 17. Results of Leak Simulation Tests Using Petro-Tite Method[a]

Tank	Baseline rate (gal/h)	Intercept (gal/h)	Bias (gal/h)	Slope	SE (gal/h)	RMS (gal/h)
Damneck	+0.003	-0.009	-0.012	1.01	0.052	0.054
Pitstop south	-2.89	-	-	-	0.240	-
north	+0.050	+0.069	+0.019	1.26	0.078	0.075
Scott 17	+0.004	+0.002	-0.002	1.075	0.036	0.036
18	-0.812	-0.774	0.038	0.608	0.109	0.115
Fort Lewis						
8C25 south	-0.342	-	-	-	0.107	-
4194	-3.0	-	(Could not fill tank)		-	-
10E10	-0.024	-0.038	-0.014	1.50	0.193	0.193
Langley golf course	-2.54	-	(Could not keep filled)		-	-

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[a] Negative = leak out; positive = leak in; bias = intercept - base.

Table 18. Sample of Simulated Leak Data for Petro-Tite Test at Scott AFB, Tank 17

Rate (gal/h)	SIM rate (gal/h)
0.004	0.000
0.044	0.000
0.004	0.000
-0.036	0.000
-0.076	-0.078
-0.076	-0.078
-0.076	-0.078
-0.060	-0.078
-0.180	-0.192
-0.160	-0.192
-0.220	-0.192
-0.076	0.000
0.080	0.000
-0.020	0.000
-0.040	0.000
-0.360	-0.321
-0.320	-0.321
-0.340	-0.321
-0.380	-0.321
-0.360	-0.321

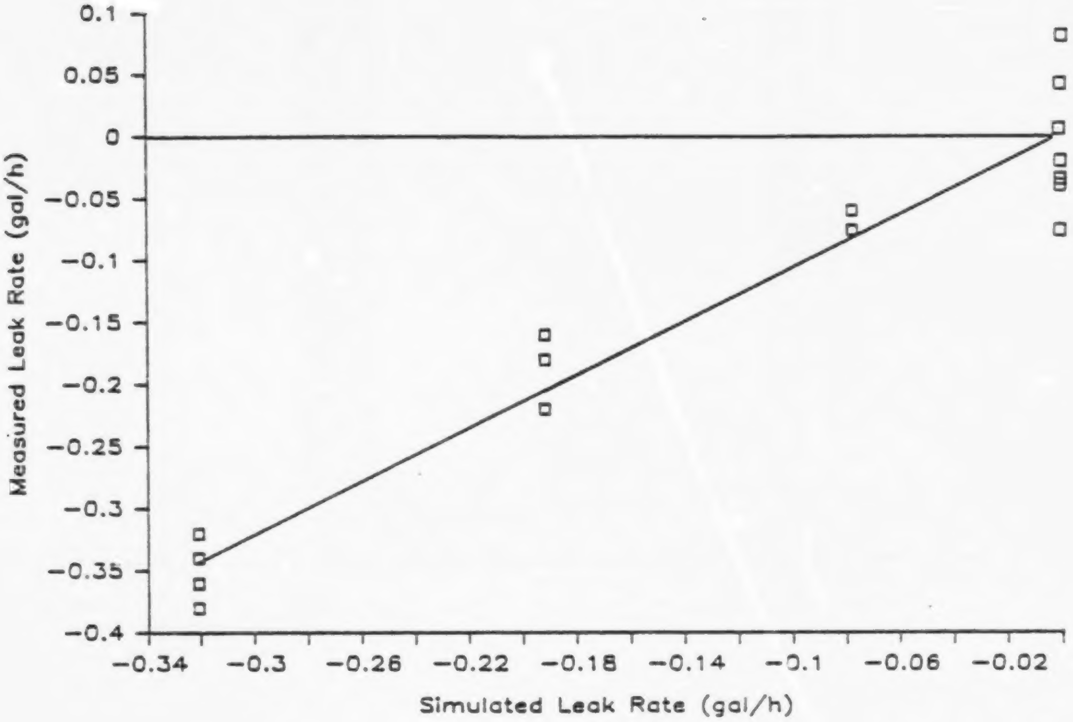


Figure 17. Simulated leak rate data for Petro-Tite test at Scott AFB Tank 17.

Although the estimated errors for the Petro-Tite method are not too large, the nature of the data suggests that they might be reduced by an alternative sampling and analysis. Clearly the error associated with a leak rate estimate can be reduced by taking additional data over a longer period of time. In addition, the procedure for temperature compensation used in the standard method is to subtract a volume change due to temperature for each period from the observed volume change. Since the temperature related volume change is subject to sampling error in the determination of the temperature change, the temperature compensated volume changes have variances that are the sum of two terms. One is from the error associated with the measurement of the volume change, and the other is from the measurement of the temperature change. Use of more frequent volume determinations, use of a larger number of volume determinations, or smoothing the temperature data before calculating the temperature correction all could reduce the error estimates.

Figure 18 is a plot of the observed volume changes each 15 min compared with the simulated leak rates from the Petro-Tite test at Damneck. Some variability of the measured volume changes about the simulated rates is apparent, but there is close agreement. Leaks out of the tank are denoted by negative values.

The temperature corrected leak rates with the simulated leak rates subtracted are plotted in Figure 19. In this case, the standard point-to-point temperature compensation used by Petro-Tite in its standard test method was used. Again, while there is some variability, the mean is close to zero and the variability is relatively small.

The cumulative volume changes and the temperature induced volume changes (also cumulative) are presented in Figure 20. This figure shows that in this tank test there was a relatively smooth temperature change and it was uniform throughout the tank. Clearly, the temperature is accounting for the volume changes except for some random error or noise. Although the point-to-point temperature compensation used by Petro-Tite worked satisfactorily in this case, the variability illustrated in Figure 19 can be reduced by a better temperature compensation algorithm.

Data from the Petro-Tite test on Fort Lewis Tank 10E10 are presented in Figures 21 through 25. Negative values denote leaks out of the tank.

This tank system test represents a case where the standard analysis was clearly insufficient. The reasons for this conclusion and a more detailed analysis are illustrated using the figures. The measured volume changes and the simulated volume changes are plotted in Figure 21. The data show considerable variability around the actual leak rates. The volume changes with the simulated leak rates subtracted out are presented in Figure 22. This figure illustrates the variability in the volume changes at 15-min intervals. The result of the temperature compensation is shown in Figure 23. In this figure both the temperature compensated volume changes (or leak rates) and the temperature compensation are shown. Two observations are apparent from the figure. First, there is a negative serial correlation between the temperature compensation and the "corrected" series. Second, the use of this method has added variability to the data. Neither of these features is desirable. Temperature adjustment should remove dependence of the data on temperature, not add it, and one wants to smooth the variability in the data, not increase it.

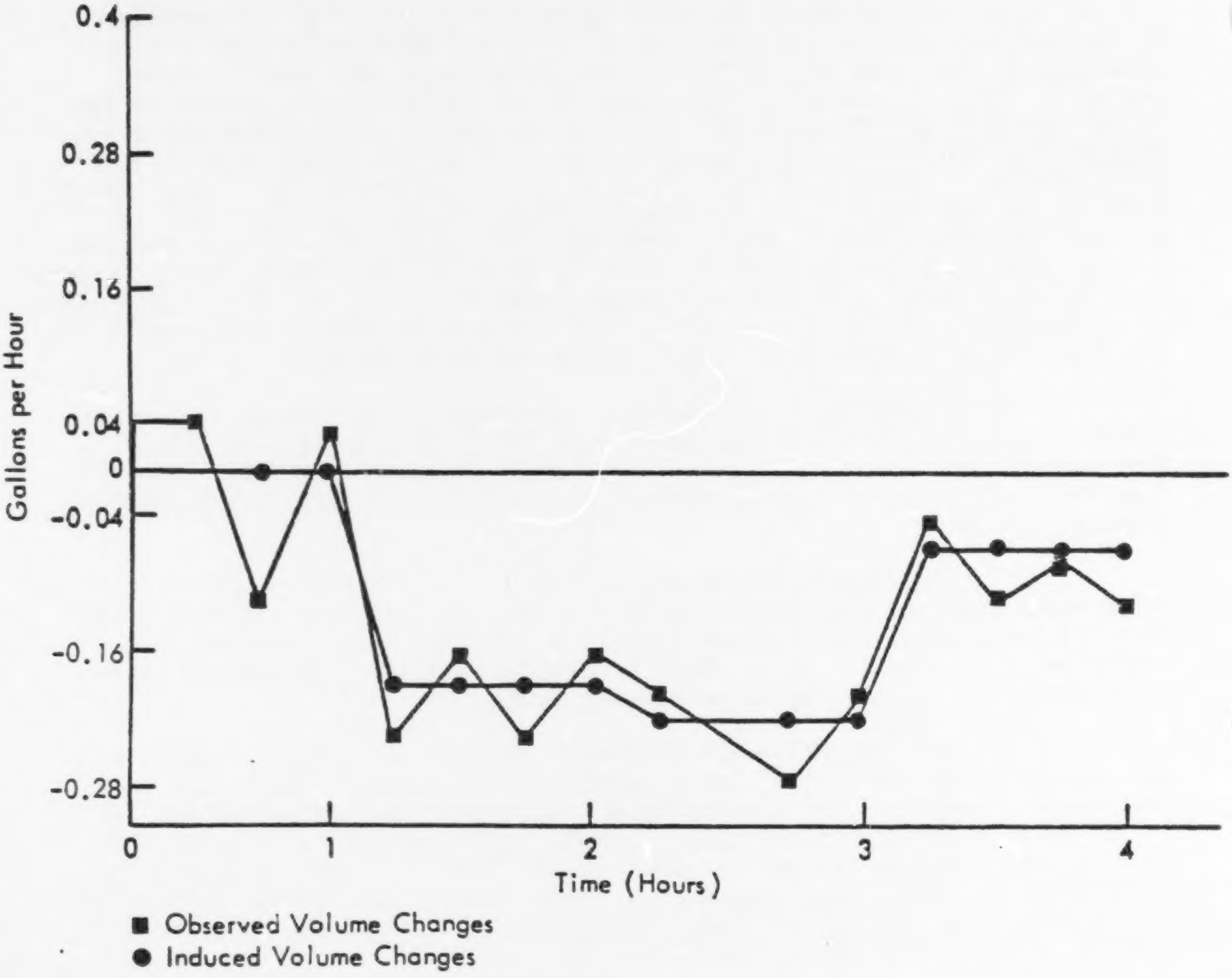


Figure 18. Measured and simulated leak rates (Petro-Tite test at Damneck).

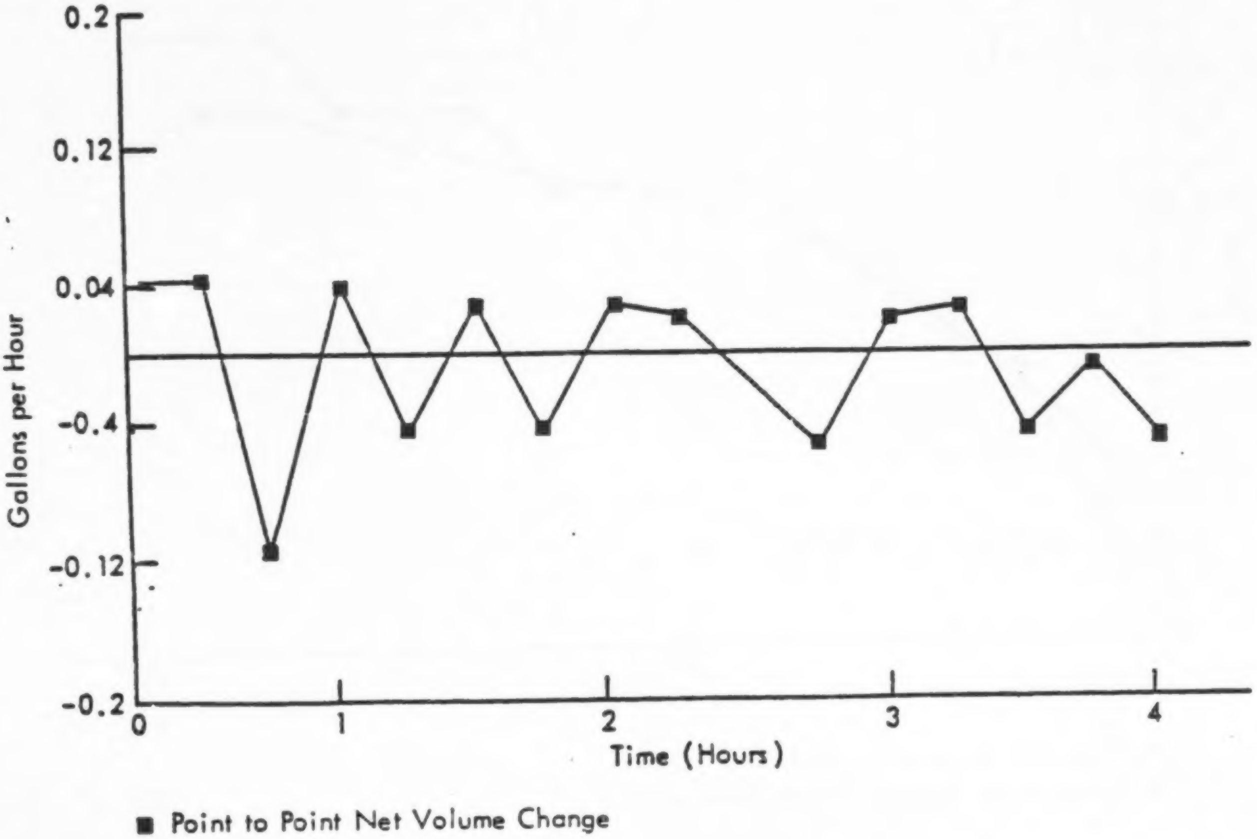


Figure 19. Temperature corrected measured leak rates (simulated leaks subtracted out) for Petro-Tite test at Damneck.

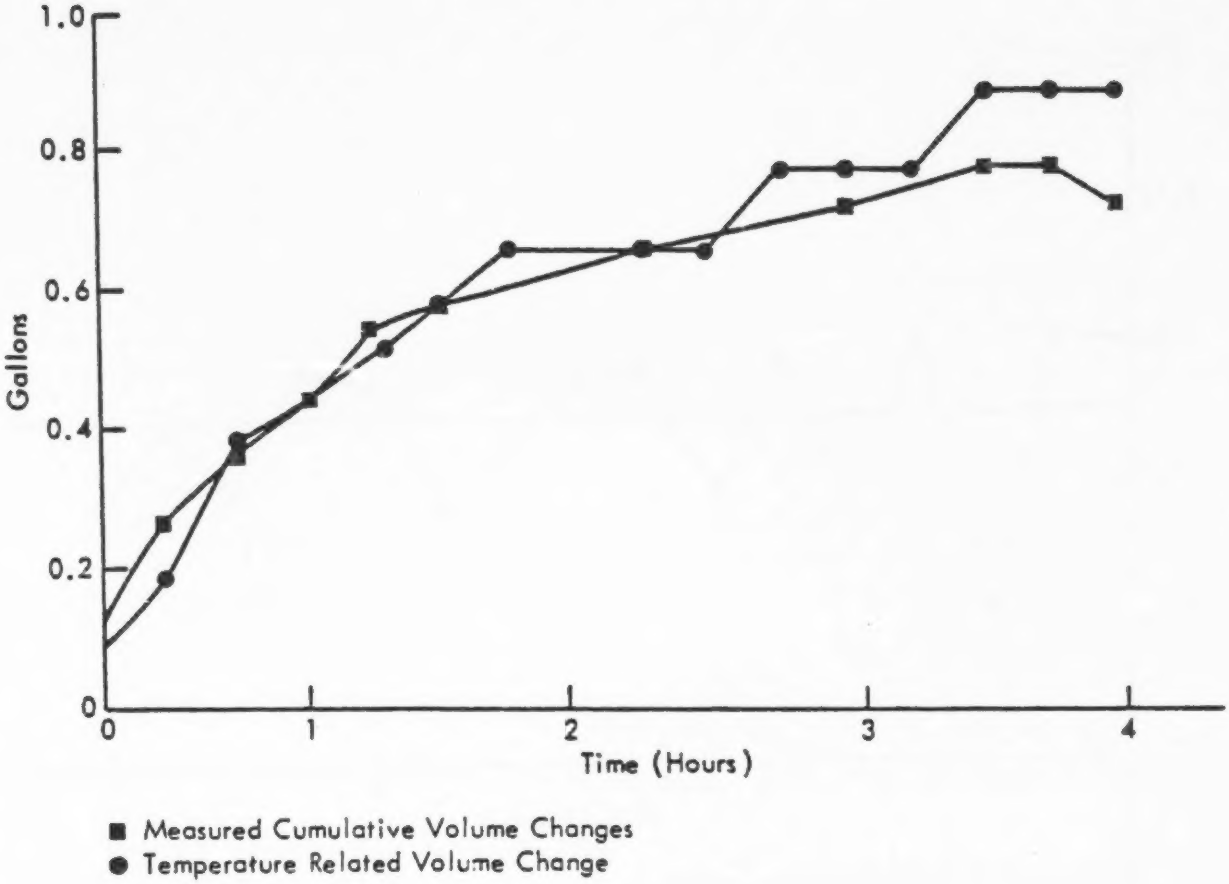


Figure 20. Cumulative measured volume changes and temperature related cumulative volume changes (Petro-Tite test at Damneck).

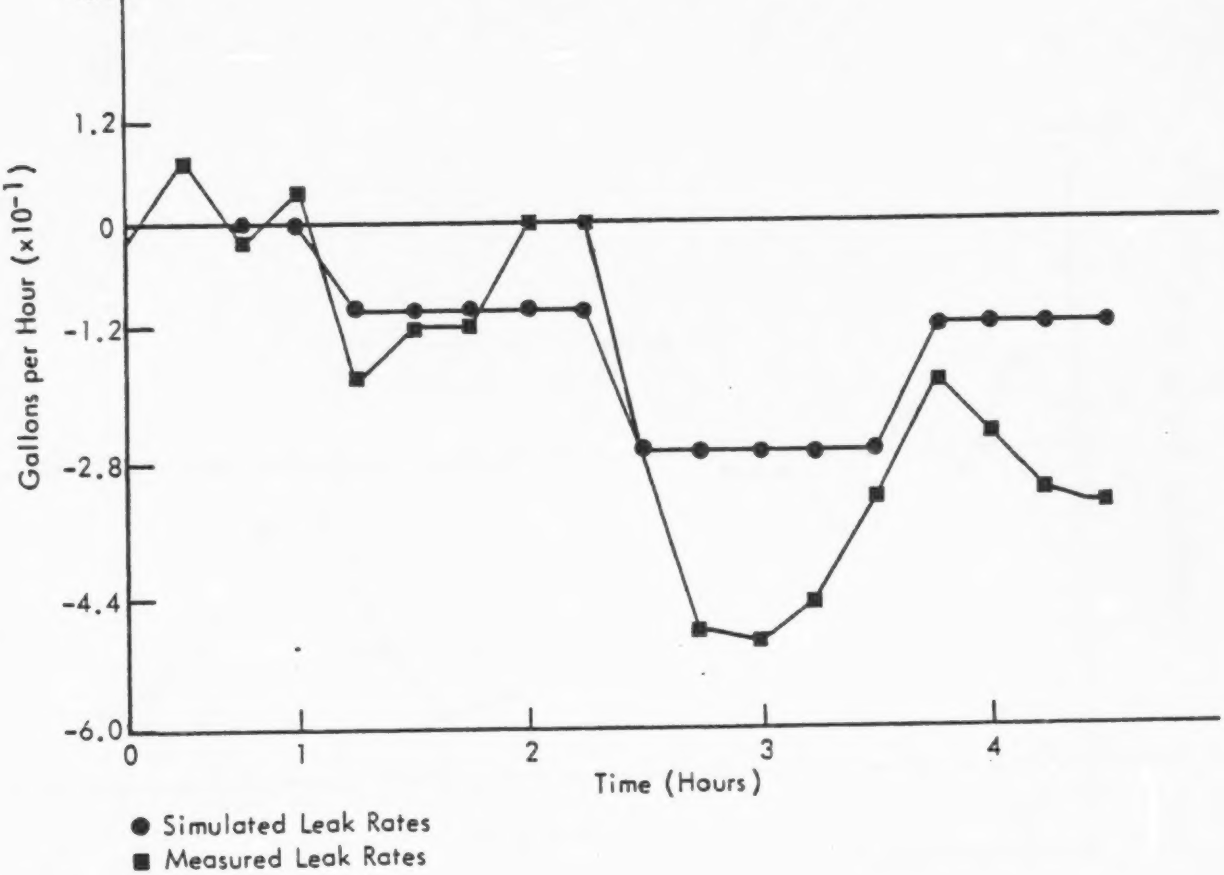


Figure 21. Measured and simulated leak rates (Petro-Tite test at Fort Lewis Tank System 10E10).

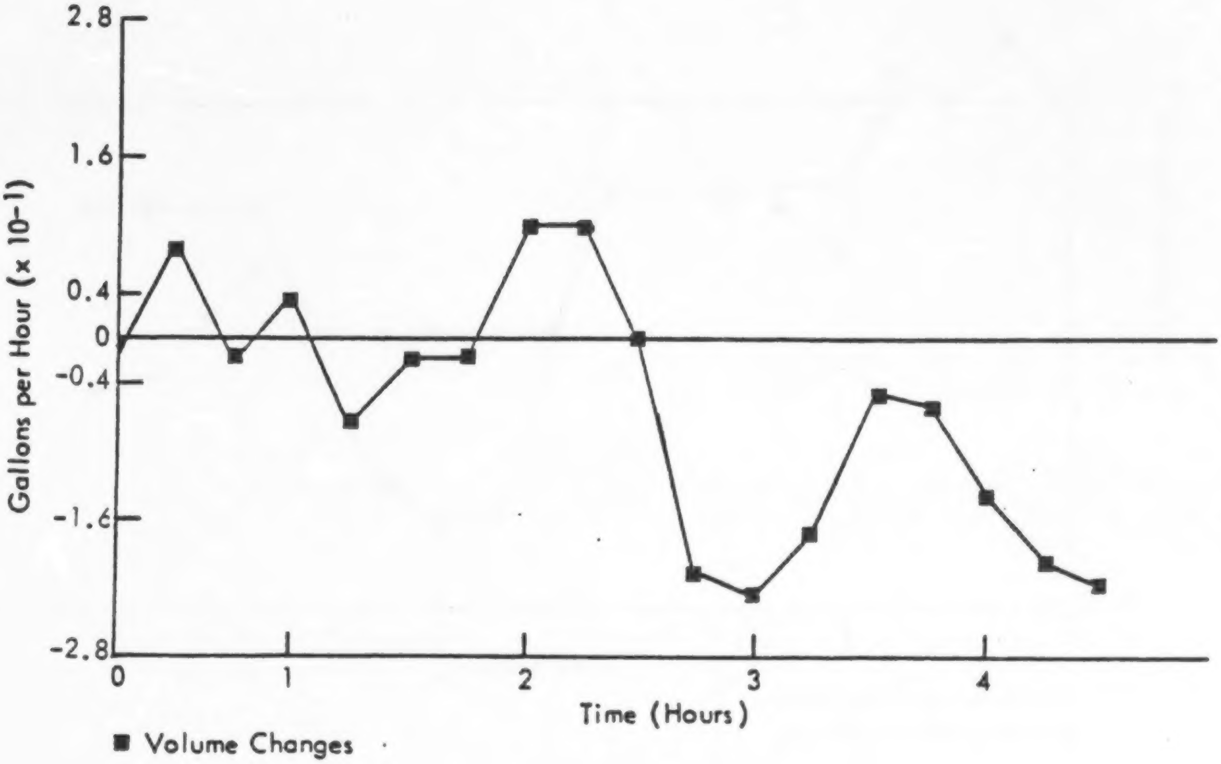


Figure 22. Measured leak rates (simulated rates subtracted out) for Petro-Tite test at Fort Lewis Tank System 10E10.

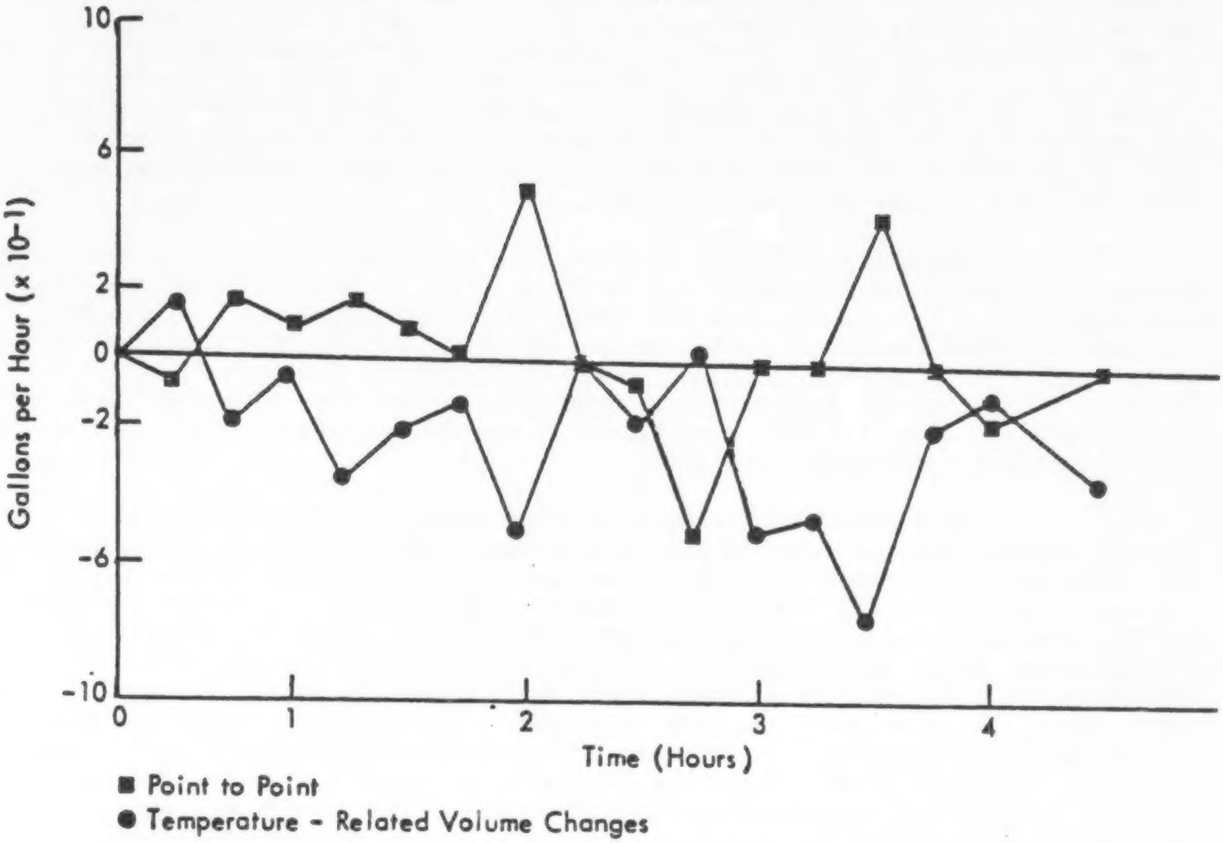


Figure 23. Point-by-point temperature compensated leak rates and temperature-volume changes (Petro-Tite test at Fort Lewis Tank System 10E10).

The temperature induced volume changes are cumulated and plotted in Figure 24. This illustrates an increasing temperature trend. A smoothing technique is used on the cumulative temperature-volume effect. This may be linear regression or a moving mean of some order. In this example, a linear regression was used. After the temperature trend has been estimated, it is used to correct the cumulative volume change. The result is plotted in Figure 25. In Figure 25 the temperature compensated cumulative volume changes are essentially zero, with little random error for the first period of about 2 h. After that point, there is a noticeable volume change, which corresponds to a leak in this case of about 0.13 gal/h.

Comparison with the original data revealed that the tank had a manway. The gasket on the manway was observed to be leaking (noted on the data sheet) at 2 h, at which time the manway bolts were tightened. After that, the gasket around the manway continued to leak product throughout the remainder of the test. This appears to be the source of the leak. Statistical tests on the first 2 h of temperature compensated data show no significant difference from zero. The leak rate reported after the manway gasket began leaking was significantly different from zero.

As a result of the more detailed analysis of Petro-Tite data, several suggestions for reducing errors involved in the method were developed. One approach is to extend the time of the test, collecting more data to reduce the error associated with the average leak rate measurement. A second approach is to increase the amount of data by making the volume change and temperature change measurements more frequently. There is a practical limit to this improvement; as the frequency of measurement is increased, some reduction in error size will occur until the error involved in releveling or measuring the volume begins to dominate. Attempts to obtain data more frequently would then result in increased error. A third approach is to smooth the volume and temperature data before incorporating the corrections. This would be a more sophisticated algorithm for data analysis and would not require other procedural changes, although maximum error reduction would be achieved through a combination of these changes. Different smoothing methods could give slightly different error modifications. The approach selected by MRI for standard analysis of the data on the national survey is described next.

The observed volume changes are accumulated. Temperature changes as measured by the thermistor are converted to equivalent volumes and these temperature-related volumes are also accumulated. By the nature of this process, both of these cumulative curves must pass through the origin. A straight line is fit to the temperature-related volume data through the origin by least squares. The predicted values from this line (smoothed temperature effects) are used to correct the observed volume for temperature. This is accomplished by subtracting the smoothed temperature effect from the observed volume. The resulting temperature corrected volumes are converted to gallons per hour by dividing by the time interval. The arithmetic mean and standard error of the mean are calculated. The arithmetic mean is the estimate of the leak rate.

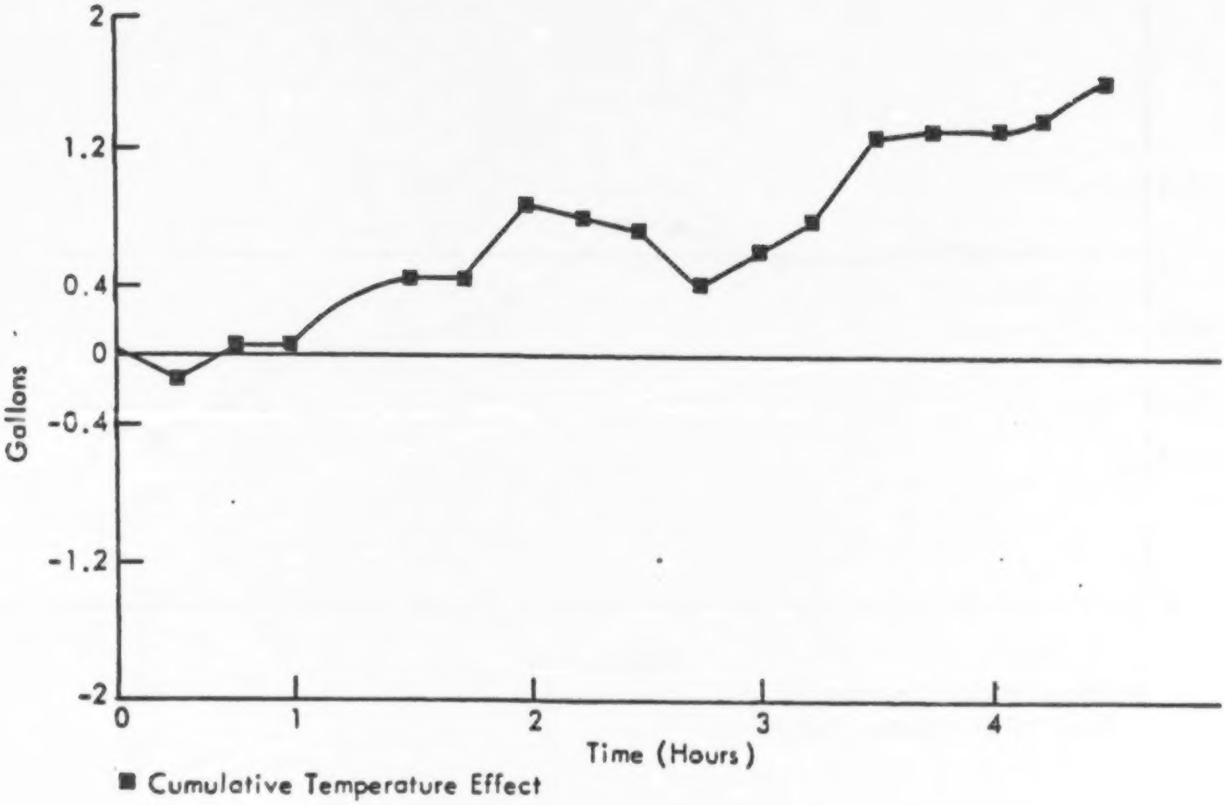


Figure 24. Cumulative temperature related volume changes (Petro-Tite test at Fort Lewis System 10E10).

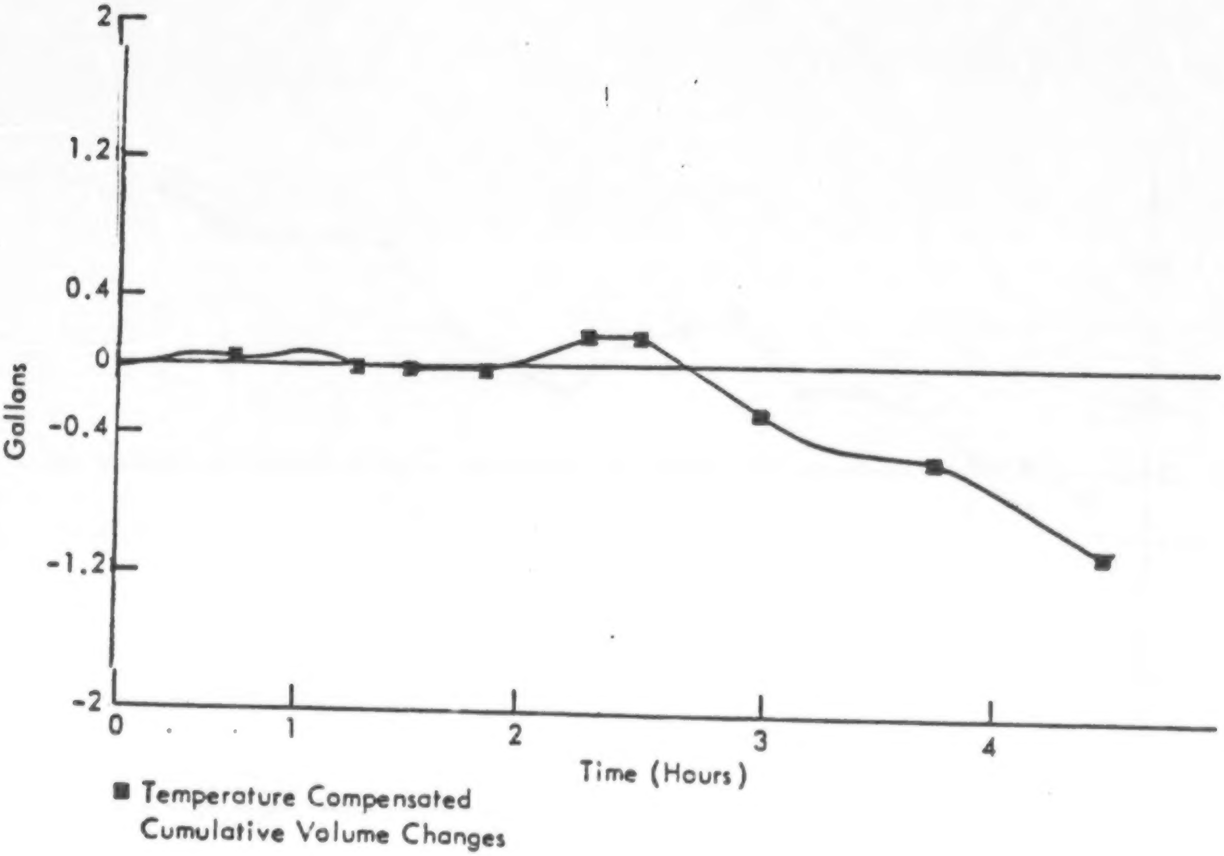


Figure 25. Cumulative volume changes (gal x 10^{-1}) after removing smoothed temperature trend (Petro-Tite test at Fort Lewis System 10E10).

A set of diagnostic procedures was implemented to ensure that the line fit the temperature data adequately. If curvature or evidence of lack of fit was found, special analysis was done for that tank. These techniques might involve using a quadratic curve to fit the data or using moving mean smoothing before the temperature correction was done.

The rationale for smoothing only the temperature data follows. The volume changes must reflect the sum of any thermal expansion or contraction plus the losses resulting from any leaks. Thus, the volume measurements are based on an integrated average temperature behavior. However, the temperature measurements are made by a single thermistor at a single point in the tank. The circulation of the product brings different product by this fixed point. Consequently, any differences in temperature on a microscale will be noted by the thermistor to its degree of response (about 0.003°F). Thus, the temperature-related volume data to be used for temperature compensation is based on a local effect rather than the whole tank average. As a result, it would be expected to be more variable than the volume data. Consequently, smoothing the temperature data to make it comparable to the integrated average of volumes over the tank is appropriate.

The Petro-Tite method seems capable of identifying and successfully dealing with many types of interferences in tank testing. Although there are situations that can lead to invalid test results, for the tanks tested in this study valid tests were always obtained. However, difficulties were encountered that increased the error associated with the estimated leak rates beyond that which is desirable. In difficult cases, large error rates rendered measurements on the order of 0.05 gal/h unreliable. In addition, large error rates were often associated with large leaks. Most of the situations with large error estimates were cases where a substantial leak was present. The leak was sufficiently large that the loss in precision did not interfere with the detection of the leak.

4. Ambient Noise Analysis Results

Since insufficient data from the ARCO tests were received to be able to perform ambient noise analysis, only the Leak Lokator and Petro-Tite results were analyzed using this technique.

a. Leak Lokator

A summary of the mean and 95% confidence intervals on the mean volume rate, temperature rate, and temperature compensated volume is presented in Table 19. The site, tank number, duration of the test sequence, the number of Leak Lokator volume rate measurements in the test sequence, and the test results based on Leak Lokator's 0.05 gal/h criterion are also given. For comparison, the baseline test results are shown. Several observations about the data presented in Table 19 are noteworthy. First, the test sequences for each tank tested are internally inconsistent. The results from five of the six tanks tested could be declared tight or leaking depending on which data sequence was used. The results of the other tank test (Fort Lewis Tank No. 3) indicate that the tank is leaking, but it could not be determined whether the flow is into or out of the tank. Second, temperature, volume, and temperature

Table 19. Summary of the Leak Lokator Analysis

Location	Tank	Test sequence	Total time (min)	N	Volume rate (gal/h)		Temperature-volume rate (gal/h)		Temperature compensation volume rate (gal/h)		Test result
					$\bar{x}$	95% CI	$\bar{x}$	95% CI	$\bar{x}$	95% CI	
Damneck	2	Baseline	1		-0.077						Leaking out
		1	101	8	-0.051	0.004	-0.011	0.007	-0.040	0.008	Tight
		2	112	9	-0.015	0.007	-0.052	0.011	0.037	0.013	Tight
		3	93	8	0.043	0.027	-0.041	0.005	0.084	0.027	Leaking in
		4	59	5	-0.028	0.010	-0.023	0.011	-0.005	0.015	Tight
Fort Lewis	2	Baseline			-0.027						Tight
		1	44	4	0.017	0.014	0.215	0.059	-0.198	0.061	Leaking out
		2	25	3	-0.044	0.028	0.096	0.096	-0.140	0.100	Leaking out
		3	40	4	0.019	0.020	0.001	0.026	0.018	0.032	Tight
Fort Lewis	3	Baseline			-0.172						Leaking out
		1	37	5	-0.130	0.012	0.043	0.004	-0.173	0.013	Leaking out
		2	35	5	-0.089	0.031	-0.001	0.010	-0.088	0.032	Leaking out
		3	43	7	-0.042	0.020	-0.104	0.041	0.062	0.046	Leaking in
Fort Lewis	4	Baseline			-0.191						Leaking out
		1	56	6	-0.203	0.052	-0.251	0.041	0.048	0.066	Tight
		2	41	6	0.157	0.068	-0.031	0.014	0.188	0.070	Leaking in
		3	41	5	0.158	0.034	-0.003	0.010	0.161	0.036	Leaking in
Pitstop	2	Baseline			-0.012						Tight
		1	48	7	0.096	0.009	0.079	0.033	0.017	0.035	Tight
		2	44	4	0.053	0.005	0.006	0.078	-0.003	0.079	Tight
		3	47	6	0.054	0.007	0.057	0.078	-0.003	0.079	Tight
		4	56	5	0.053	0.005	0.221	0.045	-0.168	0.045	Leaking out
Scott AFB	1	Baseline			-0.299						Leaking out
		1	55	6	-0.323	0.029	-0.262	0.075	-0.061	0.080	Leaking out
		2	44	6	-0.225	0.008	0.032	0.008	-0.193	0.011	Leaking out
		3	56	5	-0.241	0.005	-0.008	0.024	-0.233	0.024	Leaking out
		4	36	5	-0.206	0.0374	0.008	0.014	-0.214	0.040	Leaking out

compensated volume rate data exhibit a large range of variability compared to 0.05 gal/h. The high variability in the temperature compensated volume rate suggests that the test time is too short and a single thermistor is not adequate for measuring the mean temperature change in the tank. These conclusions are based on the raw Leak Lokator data and an analysis similar to that used by Leak Lokator except (a) an average of four to nine Leak Lokator volume rate measurements were used instead of one and (b) the average rate of change of temperature over 1 h was determined by fitting a least squares line to 5 to 10 temperature values over the hour instead of the two end points. The uncertainty in the Leak Lokator temperature compensated volume rate results presented in Table 19 is about a factor of 5 smaller than the uncertainty of a single 10 min volume rate measurement and a two-point temperature rate measurement.

The time series plots of temperature (converted to volume) and uncompensated volume were generated for each of the 21 sequences of Leak Lokator data. Cumulative time series plots illustrate the reasons for the inconsistent test results and the high variability. The shortcomings of using a single thermistor to compensate for temperature are illustrated in Figure 26 for Pitstop Tank No. 2. Since the tank is not leaking, the volume and temperature changes should be approximately equal. Figure 26 shows the results of the first sequence of measurements on Pitstop Tank No. 2; seven volume rate measurements were combined over 48 min. The temperature compensated volume rate is 0.017 gal/h. The temperature and volume data are nearly equal, suggesting that temperature accounts, as it should, for the total volume change. The test results would not change significantly for these data if only a two-point estimate of temperature were used. Figure 26 also shows the results of a 56-min test sequence on Pitstop Tank No. 2, Sequence No. 4, starting approximately 1.5 h later. The predicted temperature compensated volume computed for these data is -0.168 gal/h, significantly different from 0.017 gal/h. Clearly, the temperature changes are not correlated with the volume changes. Because the other two test sequences on this tank are reasonably consistent with the first sequence and the volume changes are nearly uniform, it appears that the single thermistor is not adequately estimating the rate of change of temperature.

Similar results were observed in other tank tests. For example, the data from the third and fourth test sequence of the Damneck test (a tight tank although incorrectly declared leaking by Leak Lokator) presented in Figure 27 and from the first and third test sequence of the Fort Lewis Tank No. 2 tests (a leaking tank incorrectly declared tight by Leak Lokator) presented in Figure 28 illustrate the same point. The difficulty in using a two-point analysis approach is clearly obvious from Figure 29 for Sequence No. 2. Depending on which two points on the temperature line (solid) are taken to determine the slope, large differences in slopes would be estimated. Hence, the temperature compensation may be highly unreliable.

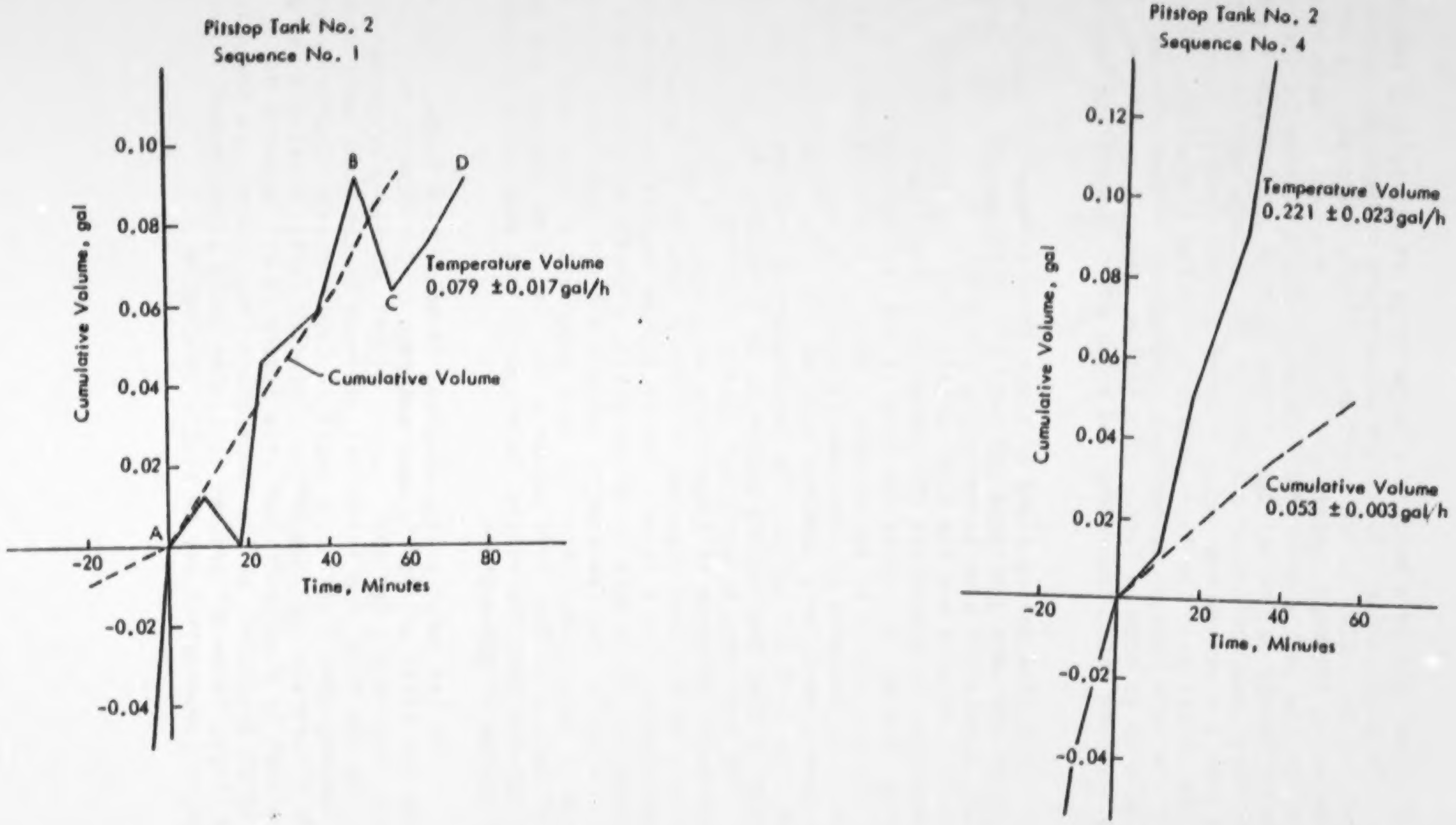


Figure 26. Time series analysis of the Leak Lokator data at Pitstop Tank No. 2.

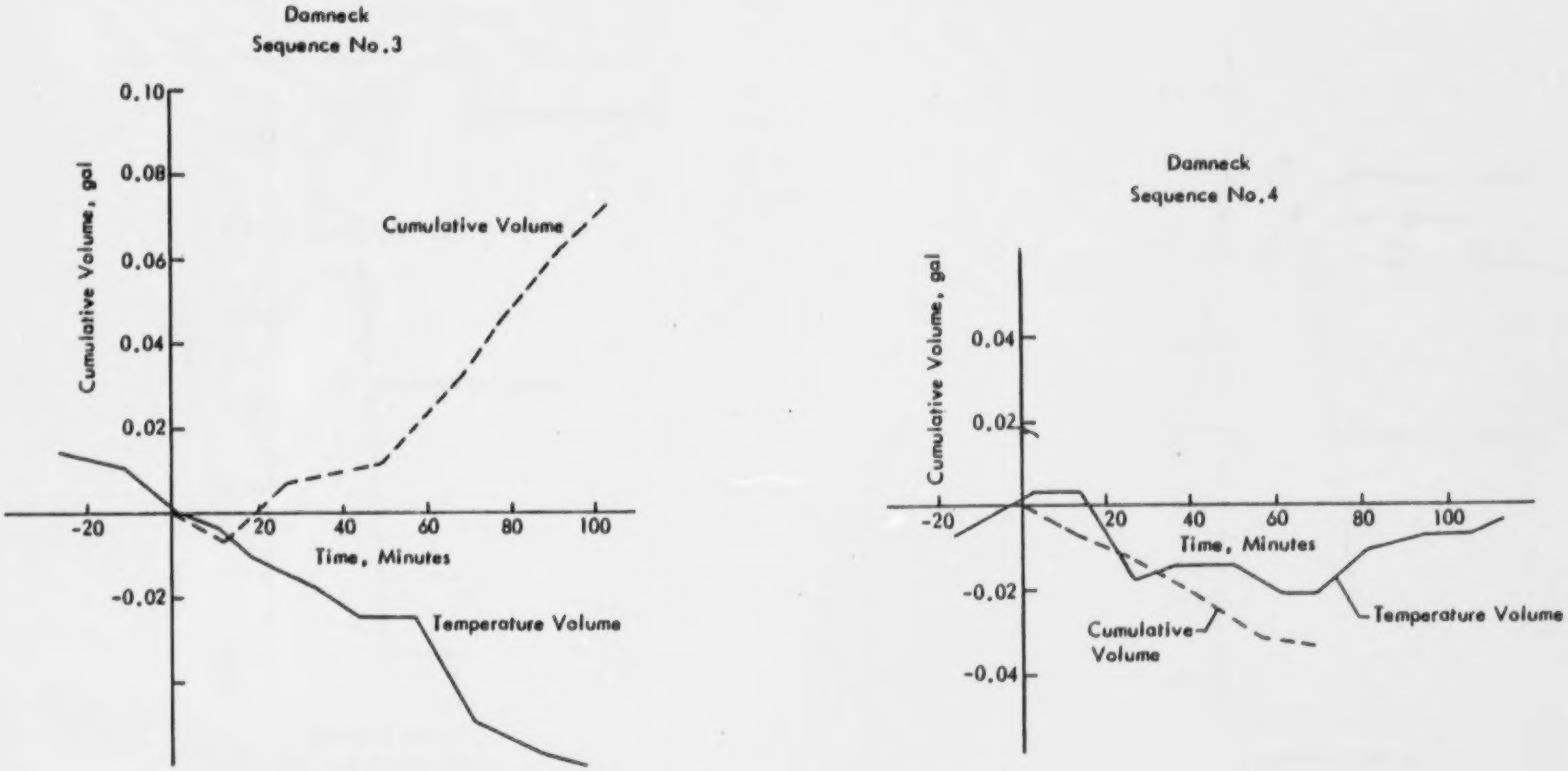


Figure 27. Time series analysis of the Leak Lokator data at Damneck.

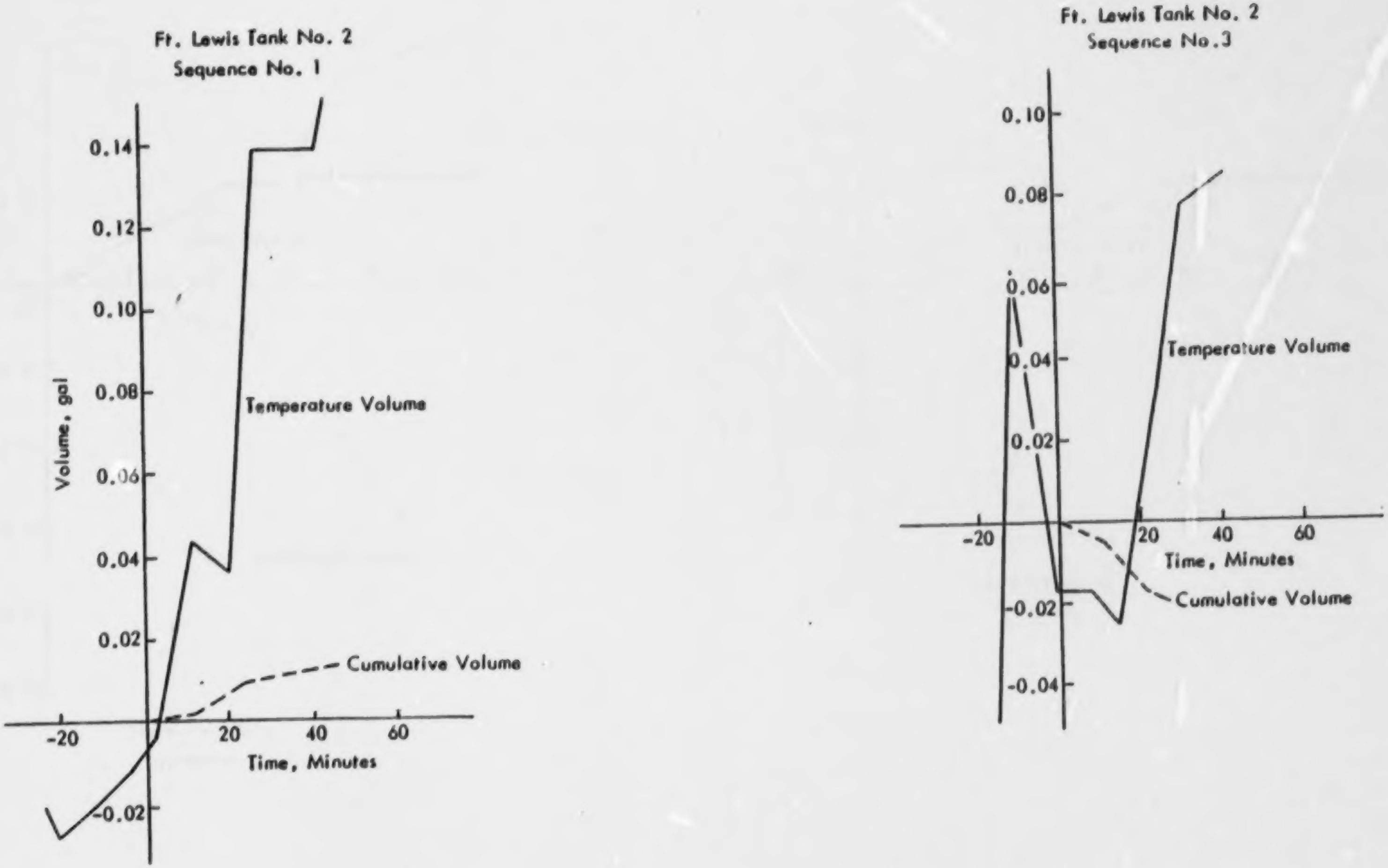
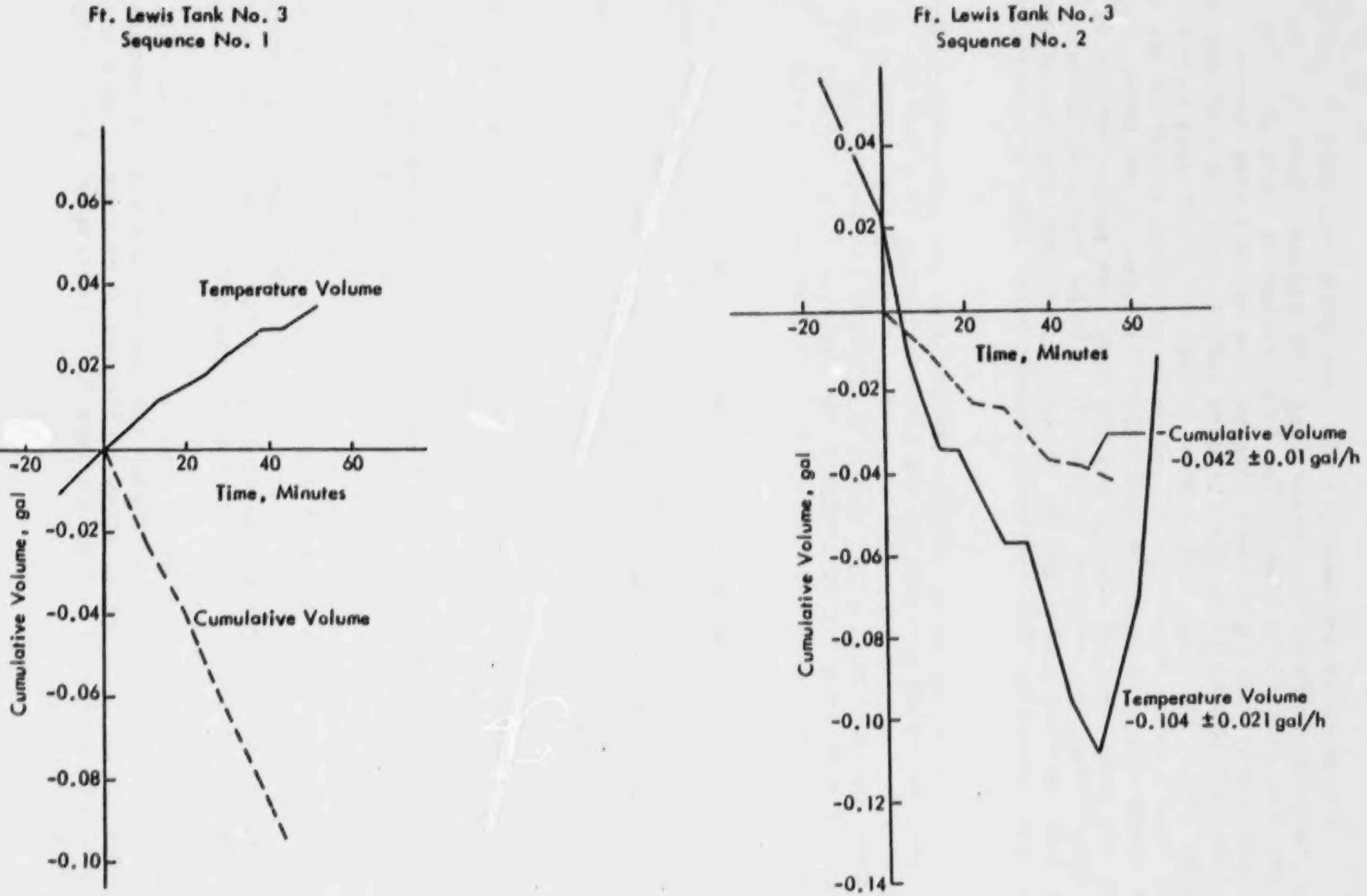


Figure 28. Time series analysis of the Leak Lokator data at Fort Lewis Tank No. 2.


Ft. Lewis Tank No. 3
Sequence No. 1

Ft. Lewis Tank No. 3
Sequence No. 2

Figure 29. Time series analysis of the Leak Lokator data at Fort Lewis Tank No. 3.

b. Petro-Tite

A summary of the mean and 95% confidence intervals on the mean volume rate, temperature rate, and temperature compensated volume rate estimated from the long Petro-Tite time series is presented in Table 20. The rates were obtained by fitting a least squares line to each time series. The confidence intervals are based on the standard deviation of the ordinate about the regression line. The site, tank number, number of 15-min data points, and the test result using Petro-Tite's 0.05 gal/h detection criterion are also given. For comparison, the baseline test result is added to the table. Agreement between the baseline test results and the long time series results is good. The one discrepancy, Pitstop Tank No. 2, will be discussed below. The time series from the Fort Lewis Tank No. 4 test was divided into two segments after a leak was identified that had begun several hours after the test was started.

The time series of volume, temperature, and temperature compensated volume, generated by removing the simulated leaks from the Petro-Tite volume-time series, are presented in Figures 30 through 33. The time series are three to six times longer than the standard 1-h Petro-Tite test. The first hour of each time series contains the baseline data. Several observations about the strengths and weaknesses of the method can be made from the data.

First, the time series for Damneck Tank No. 1 (Figure 30) and for Scott AFB Tank No. 1 (Figure 31) illustrates the high correlation between the trends of the temperature and volume data required for temperature compensation. This suggests that the method of temperature compensation, i.e., circulation of the product and measurement of the rate of change of temperature with one temperature sensor, worked adequately.

Second, negative, serial correlations were observed between the temperature and temperature compensated volume rate time series for some of the tests. This suggests that the method could be overcompensating for temperature effects. This is illustrated well by the data obtained from the Fort Lewis Tank No. 4 test data shown in Figure 32. These temperature fluctuations are probably caused by inadequate resolution of the Petro-Tite temperature sensor, although inadequate circulation or incomplete mixing could also be a cause. The sensor resolves changes of 0.003°F. A volume change of 0.021 gal would result from an temperature change of 0.003°F in a 12,000 gal tank with gasoline. This increase in the fluctuations in the temperature compensated volume data resulting from the point-to-point correction can be a problem if the test time is too short. In a short test, these fluctations can adversely influence the estimate of the trend. This is clearly observed in the baseline test conducted on Fort Lewis Tank No. 4 shown as the first hour of the data in Figure 32. Similar correlations between the temperature and the temperature compensated volume time series shown in Figures 30 through 33 were observed for the tests performed on Damneck Tank No. 1 (Figure 30) and Pitstop Tank No. 2 (Figure 33).

Table 20. Summary of the Petro-Tite Analysis

			Volume rate (gal/h)		Temperature-volume rate (gal/h)		Temperature compensation volume rate (gal/h)		Baseline test results		
Location	Tank	N	$\bar{x}$	95% CI	$\bar{x}$	95% CI	$\bar{x}$	95% CI	Test result	Temperature compensated volume rate (gal/h)	Test result
Damneck	1	20	0.043	0.008	0.064	0.008	-0.021	0.003	Tight	+0.003	Tight
Fort Lewis	2	7	-0.287	0.036	0.084	0.038	-0.371	0.050	Leaking out	-0.0342	Leaking out
Fort Lewis	4	22	-0.025	0.022	0.017	0.025	-0.042	0.027	Tight	-0.024	Tight
	4[a]	9	0.023	0.035	-0.051	0.133	0.074	0.117	Leaking in[c]		
	4[b]	13	-0.104	0.027	-0.006	0.040	-0.098	0.435	Leaking out		
Pitstop	2	19	0.151	0.010	0.013	0.009	0.133	0.011	Leaking in	-0.05	Tight
Scott AFB	1	24	0.184	0.017	0.190	0.014	-0.006	0.005	Tight	0.004	Tight
Pitstop	1	8	-2.493	0.139	0.279	0.061	-2.773	0.089	Leaking out	-2.892	Leaking out
Scott AFB	2	16	-0.714	0.024	0.009	0.005	-0.722	0.028	Leaking out	-0.812	Leaking out

[a] First 2.25 h of the test.
[b] Last 3.5 h of the test.
[c] Direction of flow only; not statistically significant from zero.

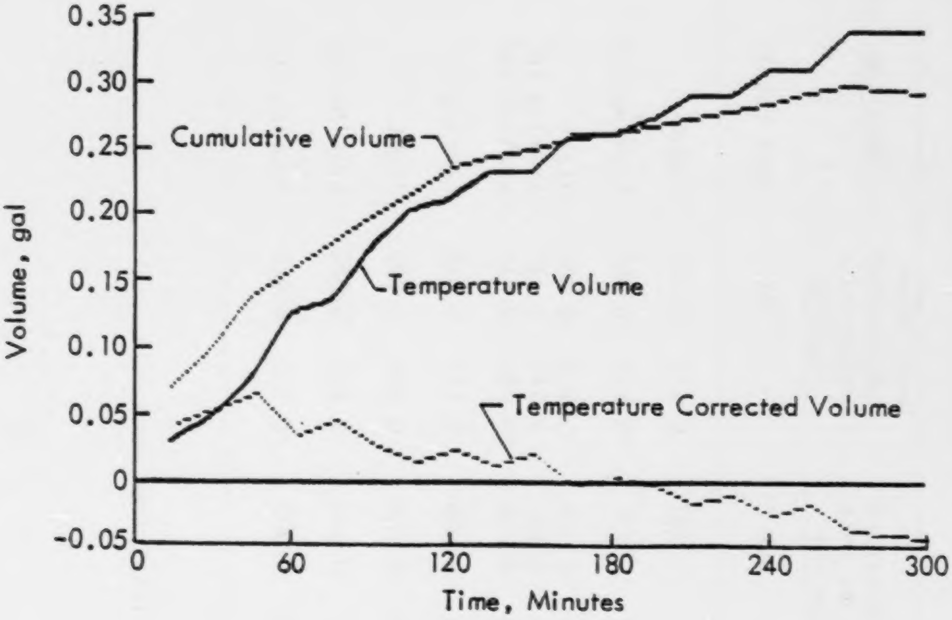


Figure 30. Time series analysis of the Petro-Tite data at Damneck Tank No. 1.

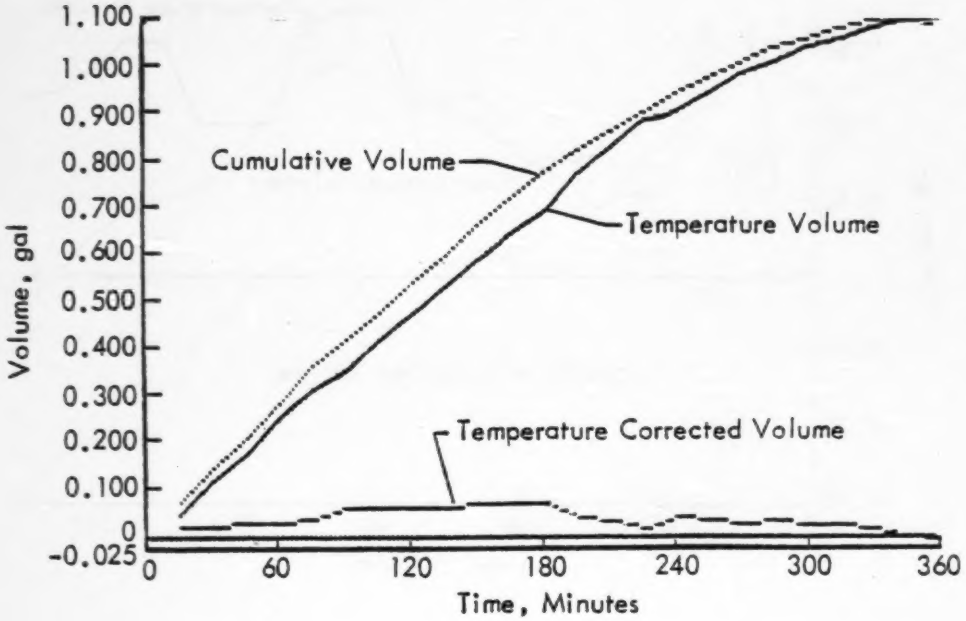


Figure 31. Time series analysis of the Petro-Tite data at Scott AFB Tank No. 1.

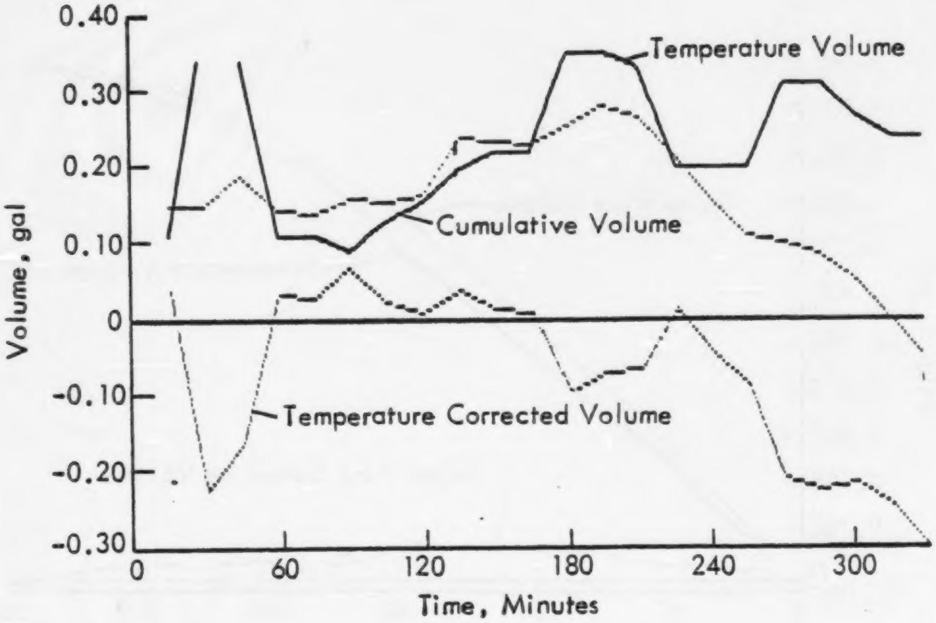


Figure 32. Time series analysis of the Petro-Tite data at Fort Lewis Tank No. 4.

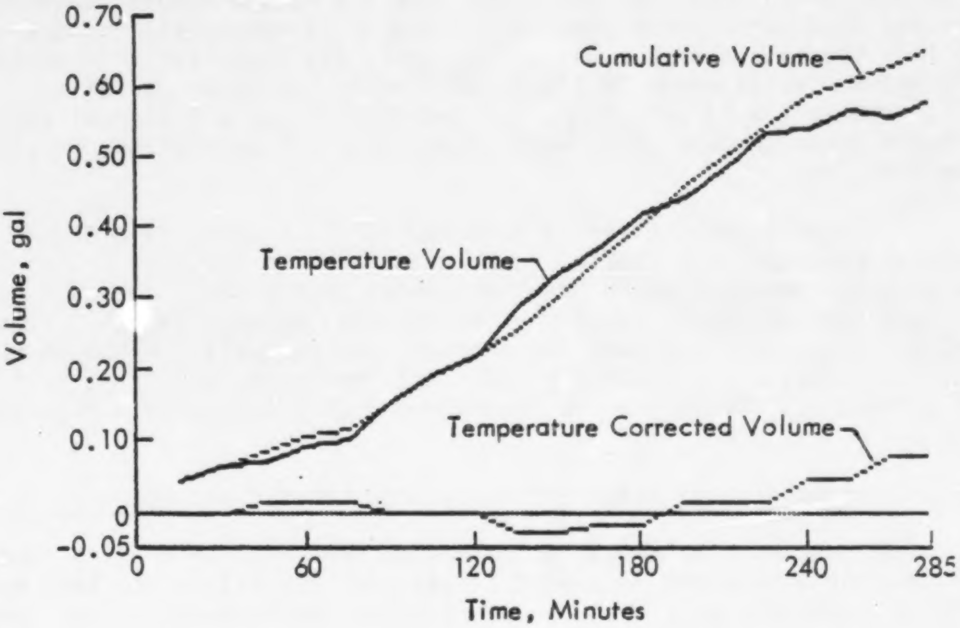


Figure 33. Time series analysis of the Petro-Tite data at Pitstop Tank No. 2.

Third, inspection of the temperature compensated volume rate time series for each test suggests that a 1-h test with data taken at 15-min intervals is too short to reliably detect small leaks. Within a test, the 15-min data show fluctations with apparent periods of 30 to 90 min. These can be sufficiently different from the trend exhibited by the entire time series to mislead the conclusions based on a 1-h test.

There is a discrepancy between the baseline and long time series test results for Pitstop Tank No. 2. The baseline test declared the tank to be tight (-0.05 gal/h) while the long time series exhibited a large inflow (0.138 gal/h) into the tank. The baseline result almost suggests that the tank may have been losing product. Since it is impossible to have water flowing into the tank during a Petro-Tite test, the test result is suspect. The 4.75-h time series shown in Figure 33 clearly indicates an inflow. The reason for the inflow is not known, but probable causes are thermal expansion of a trapped vapor pocket, inadequate measurement of temperature, or structural deformation.

The long time series obtained for Fort Lewis Tank No. 4 (Figure 32) suggests that the tank started leaking 2.25 h into the test. This is consistent with the observation in the field notes that a small leak was observed around the gasket of the manway 2 h after the test began. For this reason, the time series was divided into two segments for analysis. Although neither rate is statistically significantly different from zero, the first 2.25 h indicates a flow into the tank while the second 3.25 h indicates a flow out of the tank.

5. Precision of Measurements by Leak Lokator and Petro-Tite

The precision of measuring volume changes in a 4-in. fill tube with the Leak Lokator method and in a 4-in. riser with the Petro-Tite test method is estimated experimentally from the up and down displacements of the product level produced by inserting and removing an object of known volume. The precision, defined as the uncertainty in measuring a known volume change, is estimated from the standard deviation of the absolute value of the resulting changes in volume computed for both the up and down displacements. These types of data are collected by Leak Lokator as part of their standard tank tests for calibration of their volume measurements. Their calibration procedure requires inserting and removing a 25 cc or 50 cc cylindrical bar a total of three times before each test. The raw calibration data collected during the development study field tests are used to estimate the precision of Leak Lokator. The Leak Lokator volume data are recorded in arbitrary divisions to the nearest hundredth on a strip chart and converted to gallons using the displacement volume and the mean change on the strip chart to develop a conversion factor. Since the Petro-Tite volume measurements are made with a graduated cylinder, volume calibration measurements are not routinely made as part of their test procedure. Special calibration tests, using a 0.0555 gal cylinder, were conducted during three of the Petro-Tite Pilot Study tank tests to obtain the necessary data to estimate precision. The Petro-Tite data, sampled once per minute, were recorded in inches to the nearest hundredth and converted to gallons using the displacement volume and the mean height change to develop a conversion factor.

The results of the Leak Lokator and Petro-Tite analyses are presented in Tables 21 and 22. Each table gives the test location, tank number, displacement volume, number of displacements, and the standard deviation. The mean of the standard deviation for all the tests was obtained by taking the square root of the average variance of each test after weighting by the number of displacements. The mean and median of the standard deviations are presented in Table 23. Both methods (Leak Lokator and Petro-Tite) have more than adequate resolution for detection of 0.05 gal/h leak rates.

A difference in the magnitude of the up and down height changes was observed for two of the three Petro-Tite tests, so the mean and standard deviation of the up and down height changes were analyzed separately and are presented in Table 24. The data were converted from inches to gallons using the mean conversion factor. The data show a larger change when the product level was raised by inserting the calibration cylinder. The reason for this difference is unknown, but the difference in the means is the reason that the standard deviation computed from the combination of the up and down data is larger than the standard deviation computed for either one. This behavior was not observed in the Leak Lokator data.

E. Discussion

The important results of the development study testing are summarized below:

Each test method was applied to a wide variety of temperature profiles (see Appendix D). It is expected that all of the methods would perform best in tanks where uniform horizontal and vertical temperature changes occur. However, inadequate data exist to assess the frequency with which problems occur or to recognize the pattern produced when unstable temperature conditions are present. None of the methods that were evaluated measure temperature profiles. When erratic changes at the single thermistor are noted, additional stirring (Petro-Tite) or stabilization time (Leak Lokator) is provided. It is not known what effect erratic temperature behavior would have on the ARCO tester.

All three of the methods tested (Leak Lokator, ARCO, and Petro-Tite) measure product level and temperature with sufficient sensitivity and resolution to detect 0.05 gal/h leak rates. This can be shown by theoretical calculation and was demonstrated during the leak simulations. However, there are many factors affecting the test data which are not measured during the test (e.g., vapor pockets, unstable temperature behavior, etc.). These lower the precision and accuracy of the test. For these reasons the noise levels present during actual testing may preclude achieving consistent detection of a 0.05 gal/h leak rate. The Petro-Tite system provided the best capability for identifying problems with the test.

Table 21. Estimates of the Precision of the Leak Lokator Method

Location	Tank	Displacement volume (gal)	Number of displacements	Standard deviation (gal)
Damneck	1	0.0132	6	0.0016
	1	0.0132	6	0.0009
	1	0.0132	6	0.0003
Fort Lewis	2 (8C25 rear)	0.0132	6	0.0008
	3 (4194)	0.0132	6	0.0009
	4 (10E10)	0.0132	5	0.0017
Pitstop	2 (rear)	0.0132	6	0.0006
Scott AFB	1 (17)	0.0066	6	0.0002
Scott AFB	2 (18)	0.0066	6	0.0002
Total				0.0010

Table 22. Estimates of the Precision of the Petro-Tite Method

Location	Tank	Displacement volume (gal)	Number of displacements	Standard deviation (gal)
N30078D1	1	0.0555	17	0.0052
N29006D1	1	0.0555	19	0.0027
N29010D1	1	0.0555	18	0.0055
Mean				0.0046

Table 23. Summary of the Leak Lokator and Petro-Tite Precision Results

Test method	Standard deviation	
	Mean (gal)	Median (gal)
Leak Lokator	0.0010	0.0008
Petro-Tite	0.0046	0.0052

Table 24. Mean and Standard Deviation of the Petro-Tite Data Analyzed Separately for Up Displacements and for Down Displacements

		Increase in product level			Decrease in product level		
Location	Tank	Number of displacements	Mean (gal)	Standard deviation (gal)	Number of displacements	Mean (gal)	Standard deviation (gal)
N30078D1	1	10	0.0595	0.0016	7	0.0495	0.0013
N29006D1	1	10	0.0560	0.0035	9	0.0549	0.0015
N29010D1	1	10	0.0584	0.0059	7	0.0517	0.0018

Each method was used to test three to four leaking tanks and two to three nonleaking tanks, based on MRI's determination. The location, number, and size of the actual holes and the true leak rates are unknown. All three methods erroneously declared at least one (not the same one) of the apparently leaking tanks to be nonleaking although final analysis of the one case where this happened for Petro-Tite showed that a leak started after Petro-Tite had concluded the standard test. Leak Lokator erroneously declared three of the apparently tight tanks to be leaking. ARCO found none of the tanks to be leaking.

The test period of each test method is too short to reliably detect 0.05 gal/h leaks with acceptable probabilities of detection and false alarm.

The temperature compensation analysis algorithms are generally insufficient. However, the algorithms did provide sufficient compensation for some test conditions.

Sources of largest errors observed were test times that were too short and temperature compensation that was insufficient.

Reanalysis of the raw data over longer-than-standard test times and with different analysis techniques and compensation algorithms improved the detection performance over that obtained with standard techniques.

A single thermistor is adequate for temperature compensation only when the temperature profile changes uniformly over the entire tank over time.

The ARCO method compensates for temperature through indirectly selecting the product level. The effectiveness of the evaporation-condensation and temperature compensation method used by ARCO could not be independently analyzed from the test data.

The detection performance of each method using its standard processing algorithm varied considerably. This conclusion was based on the ambient noise and the simulated leak data.

No test operator demonstrated a consistent ability to limit on-site pretest setup time to less than several hours. Time requirements were similar for all methods.

F. Recommendations

The findings of the development study have resulted in several recommendations concerning the method of tank testing to be used in the national survey program. These recommendations were further refined, developed, and tested in the pilot study (discussed in Section V). The recommendations are summarized below.

- The tank testing method should include putting a head of pressure on the tank. There are two reasons for this. First, proper compensation for water table effects is necessary if the proper conclusion is to be reached under high water table conditions.

Second, this process enhances the flow of product through small holes making them more likely to be detected, particularly if they are near the top of the tank.

- The tank testing method should provide frequent temperature measurements with a precise thermistor and adequate temperature compensation. The product should be circulated or mixed during the test. Adequate temperature compensation is a key to successful interpretation of tank test data. Such data must consist of accurate temperature measurements at frequent intervals. The conclusion that the product should be circulated to achieve temperature uniformity resulted from the better performance observed for the Petro-Tite method over the single thermistor approach used by Leak Lokator.

- Data on temperature and level changes must be collected frequently. This facilitates the use of smoothing algorithms to more accurately determine trends and also facilitates detection and mitigation of artifacts.

- Data collection must continue longer than the standard test time so that sufficient data for a precise analysis can be provided. A longer test period with frequent temperature and level readings provides more data for trend determination. However, the practical considerations of cost and disruption to a facility will also influence the test duration.

- The test method must incorporate an adequate statistical analysis of the data to draw supportable conclusions about the leak rate. While none of the techniques was found to collect either sufficient test data or to provide adequate analysis algorithms, the Petro-Tite method was amenable to more sophisticated algorithms.

V. PILOT STUDY

A. Objectives

The results from the preliminary tests and tests at the five U.S. sites led to the recommendation that modified Petro-Tite equipment and procedures be adopted for the national survey. The major objective of the pilot study was to modify and evaluate the performance of the modified Petro-Tite method for use on the national survey. This process included testing to:

- Determine the best sampling interval for collecting the data; that is, the time interval at which product in the standpipe should be releveled and data readings made.

- Determine the best length of the test; that is, the number of data points and total time of data collection.

- Develop and test the analysis algorithm.
- Implement the procedures operationally in the field to identify operating difficulties and correct them.
- Provide data sufficient to be used on the national survey.
- Field test the entire survey data collection effort, including scheduling, data collection, and analysis.
- Finalize the test protocols.
- Estimate the detection performance of the method.

O. H. Materials under subcontract to MRI collected the data to achieve these objectives. Data analysis was performed by MRI and by Vista Research, Inc., also under subcontract to MRI (Vista 1985).

B. Overview

A sample of 25 tanks from the national survey sampling frame was selected from two primary sampling units (PSU) on the West Coast for use in the pilot study. The owners and operators of these tanks were contacted to arrange for the tanks to be tested and to schedule the tests. Timing of the contacts and arrangements for fuel delivery, payments, and scheduling presented difficulties. Recommendations for alleviating these on the national survey were developed. Notifying owners earlier of the test and giving a longer lead time to arrange and schedule the tests were found to be necessary to expedite testing.

Data were collected at three different time intervals and for three different total time periods at three sites. The resulting data were analyzed by various methods to select the most practical and effective data collection interval and test length. A standard data analysis protocol was developed for use when no testing or data problems are identified. Data management procedures for the national survey were developed. These procedures are delineated in the Test and Analysis Plan (Haile 1985) prepared for the national survey program. Data and test review procedures were developed to check each tank test for validity and to ensure that the standard analysis is adequate. A simplified analysis that can be used in the field to visually inspect the data and identify potential testing problems was developed and implemented. The tank test data were analyzed and a data report prepared and submitted to EPA.

C. Data Collection

Data identifying the tank, size, location, product, etc., were entered in a spreadsheet data file utilizing a portable computer. Following this, test data were entered as each data point became available. The spreadsheet calculations were developed to provide rapid determination of an estimated leak rate and to plot the data for visual display after a minimum number of data points had been entered. This provided a preliminary analysis and estimated volume change rate that could be obtained on the scene. The raw data from these tests and the plots and field analysis results are included in Appendix I. An example of the spreadsheet data file is shown as Table 25, and Figure 34 is the associated plot.

D. Theoretical Precision

The Petro-Tite test (discussed in Section IV.B) is based on two primary measurements. The first is the volume change in the standpipe, and the second is the temperature as measured by the thermistor arrangement. The volume is measured by bringing the product level to a reference mark by addition or subtraction of product in a cylinder graduated in hundredths of a gallon. Testing personnel try to interpolate to the nearest 0.005 gal of product, which is one source of error. The thermistor is a nonlinear device whose electrical resistance is dependent on the effects of temperature. The usual situation is that there are about 325 digits 1°F; however, this can vary to as low as 310, and a lower bound of 300 is reasonable. Thus, temperature can be measured only to about the nearest 1/300°F, a second source of error. A third source of error is the precision with which a tester can relevel the product in the standpipe. Experimental data having individual testing personnel repeatedly relevel a standpipe showed that releveling is quite reproducible. Under static conditions, the error in releveling was estimated to be about 0.00068 gal, while under actual test conditions, the error in releveling was estimated to be about 0.00270 gal.

The temperature corrected volume changes upon which the test is based are the differences of the measured volume changes and the temperature changes over the measured time intervals. As noted above, two sources of error are associated with the volume changes. Thus, the theoretical precision of the measurement can be expressed as the sum of three terms in terms of the variance of a single measurement. One variance is for the releveling precision, one for the precision with which the volume can be read, and one for the precision of the temperature measurement. The time measurements are sufficiently precise that their variability was not included.

Assuming that the error in reading the volume is a simple rounding error, if volume is rounded to the nearest 0.005 gal, the error would be that of a uniform random variable distributed on the range (-0.0025, +0.0025) gallons. The variance of a uniform random variable is given by the formula (range squared)/12. Thus the variance would be 2.083×10^{-6} gal squared. Actually, it is probably better to assume that the measurement is to the nearest 0.01 gal, as that is the finest graduation on the cylinder. This would lead to a variance estimate of 8.33×10^{-6} gal squared.

The experimental data suggest that the error involved in releveling the standpipe is also a rounding error with a variance of about 7.27×10^{-6} gal squared, or a standard deviation of 0.0027 gal.

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Table 25. Example Spreadsheet Data File

```
01-Apr-85
                                   Page 1

     Site Code L29528A     Fuel Type UNLEADED    Date          MAR.13,85
     Test Firm O.H.M.      Tank Vol          1036 T digits          11622
     Test Crew BS,DF,JS    API Dens          60.1 T digits/F          317
     MRI Crew  BC,MG       Exp Coef  0.00061431 Leak Rate         -0.002
                                                                    0.003
 Time     Level       V Before  V After    Fuel Temp  Tcorr dV Leak Rate
Hr  Min   (div)        (gal)     (gal)     (digits)    (gal)    (gal/h)
-------------------------------------------------------------------------
11  15           12    N/A       N/A          11764     N/A       N/A
11  30           12     0.500     0.575       11813     0.017     0.067
11  45           12     0.575     0.64        11843     0.005     0.019
12   0           12     0.64      0.71        11873     0.010     0.039
12  15           12     0.71      0.76        11900    -0.004    -0.017
12  30           12     0.76      0.82        11926     0.004     0.015
12  45           12     0.82      0.875       11957    -0.003    -0.013
13   0           12     0.21      0.26        11982      .000    -0.001
13  15           12     0.26      0.315       12011    -0.003    -0.013
13  30           12     0.315     0.365       12034     0.004     0.015
13  45           12     0.365     0.41        12061    -0.009    -0.037
14   0           12     0.41      0.455       12085    -0.003    -0.013
14  15           12     0.455     0.505       12107     0.006     0.023
14  30           12     0.505     0.55        12128     0.003     0.011
14  45           12     0.55      0.585       12148    -0.005    -0.021
15   0           12     0.585     0.615       12166    -0.006    -0.025
15  15           12     0.615     0.65        12185    -0.003    -0.013
-------------------------------------------------------------------------
```

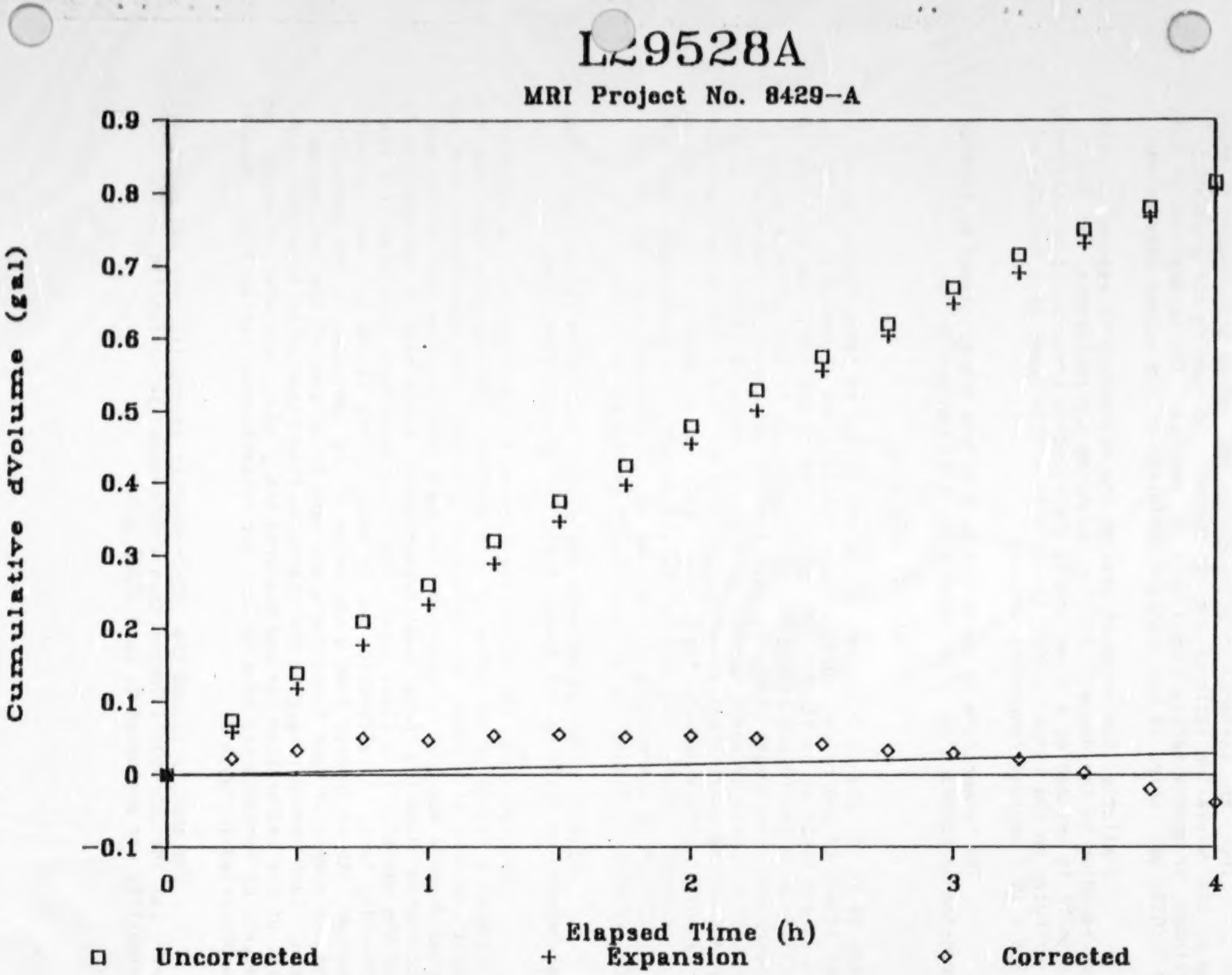

Figure 34. Sample data plot.

Thus, the variance associated with the volume measurement is the sum of the releveling variance and the variance in reading the graduated cylinder, or approximately 1.56×10^{-5} gal squared. The square root of this is 0.00395 gal, which is the standard deviation of the volume measurement.

Similarly, the error in reading the thermistor is assumed to result from rounding to the nearest digit in balancing the resistance. If 300 digits/°F is assumed as a lower bound, the rounding error would be uniformly distributed on the range -1/600° to +1/600°F. This leads to a variance of 9.259×10^{-7} degrees Fahrenheit squared.

The temperature is converted to a volume change caused by thermal expansion or contraction. The formula for this conversion is:

$$dV = dT \times Ce \times V_0$$

where dV is the change in volume, dT is the change in temperature, Ce is the coefficient of expansion, and V_0 is the total volume of product. If the Ce and V_0 are taken as constants for a given product and tank, the variance associated with the volume change due to temperature is the variance of the temperature measurement times the square of Ce and times the square of V_0. Thus, this source of error depends directly on the size of the tank. It also depends on the coefficient of expansion. The major difference in coefficient of expansion occurs between fuels, e.g., gasoline at about 0.0006 and diesel fuel at about 0.00045. For the Petro-Tite method, the temperature resolution is 0.003°F which corresponds to a volume of 0.018 gal and 0.014 gal for gasoline and diesel, respectively, in a 10,000 gal tank.

Table 26 gives approximate theoretical precision values for a single measurement for gasoline and diesel fuel, for several tank sizes.

As discussed, the Petro-Tite testing system requires the operator to relevel a standpipe periodically. In addition, the operator must read the amount (volume) of product in a graduated cylinder. Two experiments were conducted at site N29006D1 to determine how much interobserver variability was encountered in making these level measurements, which require the operator to read the meniscus in a glass tube. The first experiment consisted of a static releveling test. A calibration bar of known volume (0.056 gal) was repeatedly inserted into or removed from a standpipe of the type used in the Petro-Tite test. A sample of four individuals who were to do some of the testing was taken. Each person releveled the standpipe five times after insertion or removal of the calibration bar and measured the product recovered or added. An analysis of variance was done to test for interobserver variability. Results are presented in Table 27.

The analyis showed the inter-observer variability was not significantly (at the 10% level) larger than within-observer variability. The variability was estimated to be 0.00265 gal.

Table 26. Precision of Temperature and Volume Measurements

Volume (gal)	Standard deviation (gal) Diesel	 Gasoline
250	3.951167×10^{-3}	3.95232×10^{-3}
500	3.955613×10^{-3}	3.960219×10^{-3}
1,000	3.973349×10^{-3}	3.991658×10^{-3}
1,500	4.002733×10^{-3}	4.043514×10^{-3}
2,000	4.043514×10^{-3}	4.115014×10^{-3}
2,500	4.095348×10^{-3}	4.205156×10^{-3}
3,000	4.157824×10^{-3}	4.312772×10^{-3}
3,500	4.23047×10^{-3}	4.43659×10^{-3}
4,000	4.312772×10^{-3}	4.575297×10^{-3}
4,500	4.404188×10^{-3}	4.727579×10^{-3}
5,000	4.504165×10^{-3}	4.892171×10^{-3}
5,500	4.612144×10^{-3}	5.067873×10^{-3}
6,000	4.727579×10^{-3}	5.25357×10^{-3}
6,500	4.849936×10^{-4}	5.448242×10^{-3}
7,000	4.978705×10^{-3}	5.650959×10^{-3}
7,500	5.113402×10^{-3}	5.860888×10^{-3}
8,000	5.25357×10^{-3}	6.077281×10^{-3}
8,500	5.398785×10^{-3}	6.077281×10^{-3}
9,000	5.548649×10^{-3}	6.299471×10^{-3}
9,500	5.702796×10^{-3}	6.758945×10^{-3}
10,000	5.860888×10^{-3}	6.995237×10^{-3}
10,500	6.022614×10^{-3}	7.235331×10^{-3}
11,000	6.187689×10^{-3}	7.47886×10^{-3}
11,500	6.355854×10^{-3}	7.725499×10^{-3}
12,000	6.526868×10^{-3}	7.974961×10^{-3}
12,500	6.700513×10^{-3}	8.226989×10^{-3}
13,000	6.876591×10^{-3}	8.48135×10^{-3}
13,500	7.054919×10^{-3}	8.737849×10^{-3}
14,000	7.23533×10^{-3}	8.996296×10^{-3}
14,500	7.417673×10^{-3}	9.256529×10^{-3}
15,000	7.601809×10^{-3}	9.518404×10^{-3}

Table 27. Analysis of Variance for Interobserver Variability

Source	Sum of squares	df	Mean square
Observers	2.190471×10^{-6}	3	7.301569×10^{-7}
Error	4.813075×10^{-6}	12	4.010896×10^{-7}
Total	7.003546×10^{-6}		

F-test ratio 1.820 - not significant at 10%.

Note: $S = 2.65 \times 10^{-3} = 0.0026$ gal.

Another source of variability is present in the actual testing in that the level changes as temperature or other variables in the tank change, which may introduce additional variability into the volume measurements. Ten releveling calibrations with the calibration bar were done on each of two tanks during testing to determine the size of the variation. The pooled estimate of variance from these dynamic trials was 7.270 x 10^{-6}, somewhat larger than the estimate from the static releveling tests. Expressed on the same scale as the measurements (by taking the square roots), the variability estimated from the static tests was 6.833 x 10^{-4} gal, while that from the dynamic releveling tests was 2.696 x 10^{-3} gal. This latter number is probably the best estimate of total variation in the volume measurement process because it includes interobserver variation, replication, and some variation due to differences in the two tanks under test. However, there is probably more variation due to differences in the environment and among tanks than is represented in the variability between these two tanks. Thus, this variability should be regarded as not including tank-to-tank variability.

E. Data Analysis

The data from the pilot study tank tests were analyzed with several purposes in mind. One was to determine the best sampling interval. Data collection intervals of 1, 5, 10, and 15 min were considered. Data collection at 1-min intervals was found to be impractical for the large scale survey. For the 1 min data, it appeared that the additional reduction in standard error that would result from the more frequent data was lost because of the additional difficulties in reading accurately in the short time available. In addition, analysis performed by Vista Research, Inc. (Vista 1985) on the 1-min data suggested that the time to independence was about 4 min. That is, measurements needed to be about 4 min apart in order that they not be serially correlated. Consequently, use of time intervals less than about 5 min might result in dependence.

Since the standard error of the estimated leak rate is proportional to the square root of the number of observations, both the 5-min and 10-min intervals would provide improvements to the precision of the test data. The tests on the pilot study with 15-min intervals gave an average standard error of 0.0223 gal/h, while the tests with 5-min intervals gave an average standard error of 0.014 gal/h. Both of these standard errors are computed for a total test time of 2 h. Theoretically, the 5-min times should reduce the standard error by a factor of 1/(1.732) or should multiply the standard error by 0.577. The actual reduction obtained with the 5-min data was slightly less than theoretical. That observed was 0.014 gal/h, while the theoretical value would be 0.0129 gal/h. The difference may be due to chance, or it may suggest that the 5-min interval is about at the limit of the observers. Spectral analysis by Vista Research, Inc., also indicated that the 5-min interval is an optimum sample interval.

The 10-min interval was not used in the pilot study. It would theoretically reduce the standard error of the leak rate by a factor of 0.82 compared to that of the 15 min interval for the same total test time. However, it is inconvenient for the test crews to use because its intervals do not coincide with the 15-min test intervals that are standard. For this reason and the improved precision provided by the 5-min interval, it was decided to not use the 10-min interval.

The pilot study results demonstrated that data collection at 5-min intervals was practical in the field. Further, the analysis of the 1-min data indicated that a 5-min interval should generally result in independent observations. The expected improvement in precision was observed on the pilot study. As a result of these considerations, the 5-min interval was recommended as the standard for the national survey.

Determination of the best total time of the test was not so clear-cut. Precision and accuracy can be improved by longer test times, but this is achieved at the expense of more inconvenience for the owner/operator and longer work days for the test crew. Long test times would necessitate duplicate crews or would result in loss of data because of increased errors caused by fatigue. A compromise of 2 h of data at the low level was selected as providing sufficient data while still proving to be practical for the field data collection.

Seventeen of the 25 tanks selected were tested in this pilot study. The remaining 8 tanks could not be tested due to scheduling problems or other limitations. The data from these tank tests were analyzed to estimate whether a tank was leaking and to provide an estimated volume change rate together with its estimated standard error. The results of the final analysis for each tank were reported on a site data summary form, an example of which is shown in Figure 35.

A summary of the test results is presented in Table 28. To be consistent with national survey results, the standard errors are all reported for 2-h test times. Four tanks had data collected at 15-min intervals and so had larger standard errors. Two tank tests are not included because of data problems that indicate testing difficulties that may invalidate the results. These tanks were at sites N3000000078 and N290000010 (tank 2 of 3).

The data reported in Table 28 express the leak rates in gallons per hour. The standard errors reported are in the same units. In addition to the quantitative leak rate estimate, a qualitative (yes or no) determination is also presented. The conclusion about leaking or not is coded as "C" for certifiable, that is, not leaking by the 0.05 gal/h NFPA standard. A code of "N" is used for noncertifiable. If the "N" is followed by (I), the tank could not be certified by the test, but there were problems with the test that made the results invalid.

Three of the systems had leaks. Two were fairly large (-1.381 gal/h and -0.263 gal/h), while one was smaller (-0.107 gal/h). One additional system had a system leak rate (-0.056 gal/h) even though the tank was certified by the Petro-Tite test crew, who estimated a leak rate of -0.029 gal/h (later found to have been taken when the tank was isolated from the line). Detailed analysis of the data from this system revealed that the leak rate of -0.056 gal/h for the system was due to a leaking delivery line. The line test gave a line leak rate of -0.04 gal/h. When the tank was isolated from the line, the tank rate was -0.018 gal/h. It was concluded that the system leak consisted of the line leak and that the tank was tight.

SITE DATA SUMMARY

Survey ID No. L290000528

Tank No. 1 of 2

Tank Size 1036 Gal.

Test Date Mar 13, 1985

Product Unleaded

TEST RESULTS

	System	Line 1	Line 2	Line 3	Line 4
Certified	Yes	N/A			
Rate	-0.01				
S.E.	0.0098				

Figure 35. Example data summary. Note: The standard error reported has been adjusted to a 2-h test period for consistency with future tests on the national survey. A negative sign indicates leak out of tank.

Table 28. Summary of Pilot Study Results

Site no.	Tank no.	Tank size (gal)	Fuel	System[a] leak rate (gal/h)	SE (2 h) (gal/h)	Standard Petro-Tite result (gal/h)	Conclusion
N290000006		11,907	UNL	0.036	0.0074	+0.037	C
N310000561	T1	1,034	UNL	-0.036	0.0098	-0.038	C
L310000561	T2	7,896	D	-1.381	0.0490	-1.518	N
L310000561	T3	7,896	D	-0.263	0.0138	-0.367	N
L310000561	T4	10,152	D	0.009	0.0107	+0.015	C
L310000567		1,036	PUNL	-0.012	0.0242	+0.032	C
N300000078		10,152	UNL	0.188	0.058	+0.256	N(I)
G310000464	T1	10,152	D	0.026	0.0114	0.042	C
G310000464	T2	10,152	D	-0.107	0.0041	-0.115	N
G310000464	T3	10,152	UNL	0.052	0.0047	-0.005	C
N310000109		8,000	UNL	-0.008	0.0137	-0.024	C
N290000010	T1	6,006	LR	0.036	0.0245	+0.016	C
N290000010	T2	6,006	LP	0.042	0.0307	+0.096	N(I)
N290000010	T3	6,006	UNL	0.013	0.0348	+0.031	C
G290000123		10,383	D	-0.056	0.0067	-0.029	N
N290000528	T1	1,036	UNL	-0.002	0.003	+0.028	C
N290000528	T2	1,036	LR	-0.014	0.0130	-0.008	C

C = certifiable by NFPA standard; N = not certifiable; (I) inconclusive test; D = diesel; UNL = unleaded; PUNL = premium unleaded; LR = leaded regular; LP = leaded premium.

[a] Estimates from modified Petro-Tite test with revised data collection and analysis.

Of the 17 tanks tested, one resulted in a clearly invalid test. One test was problematical, but the system was probably tight. Three tanks appear to have significant leaks, and the remainder appear to be tight. It should be noted that the leak rates reported here are the leak rates or volume change rates observed under the testing situation, which includes a positive pressure of 4 psi at the bottom of the tank. Since this is higher than the pressure found in the tank during normal operating conditions, the ability to detect leaks is enhanced. Thus the volumes of product escaping into the environment would be smaller in actual tank operation. Depending on the location of the hole where the tank is leaking, the leak rates could actually be as low as zero in operation; for example, if the hole is in the top of the tank and the system never has product at that level. These rates, then, are overestimates of product loss or leakage in operation.

A preliminary estimate of the performance of the test can be made from the pilot data. The estimate is preliminary for three reasons. First, only a limited number of tanks were tested. Second, since these were in a restricted geographical area, the results may not be representative of the nation as a whole. Third, in fine-tuning the sampling frequency to optimize test performance, not all tank data were collected at the sampling frequency finally determined for the modified method. Consequently, the estimate of the performance is preliminary and the actual performance of the test method on the national survey may differ.

The performance of the test method is primarily determined by the standard error of the leak rate estimate. With a given threshold for declaring a leak, or for a specified allowable probability of type I error, the standard error can be used to calculate a performance curve. In this context, a type I error is a false alarm, that is, declaring a tight tank to be leaking. The power is the probability that the test would detect a leak of a given rate. The standard errors of the estimated leak rates on the pilot study ranged from 0.01 gal/h to 0.035 gal/h for tanks that had valid tests and that were tested with the 5 min protocol. Consequently, a value of 0.03 gal/h for the standard error is a reasonable estimate for the performance of the test.

Using this and the NFPA Standard 329 criterion of 0.05 gal/h as the threshold for declaring a leak yields the performance curve plotted as Figure 36. In Figure 36, the probability of detection or power is plotted as a function of the true leak rate. The significance level is the point where the curve crosses 0, denoted by the vertical line. This is the probability of a false alarm. This curve is an estimate of the performance of the test to be used on the national survey. At the threshold value of 0.05 gal/h the probability of detecting a leak of exactly 0.05 gal/h is 50%. At this threshold (0.05 gal/h) a leak rate of 0.10 gal/h would be detected with a probability of approximately 95%. The probability of detecting a leak depends on the size of the leak, the threshold, and the variability of the data from a particular tank.

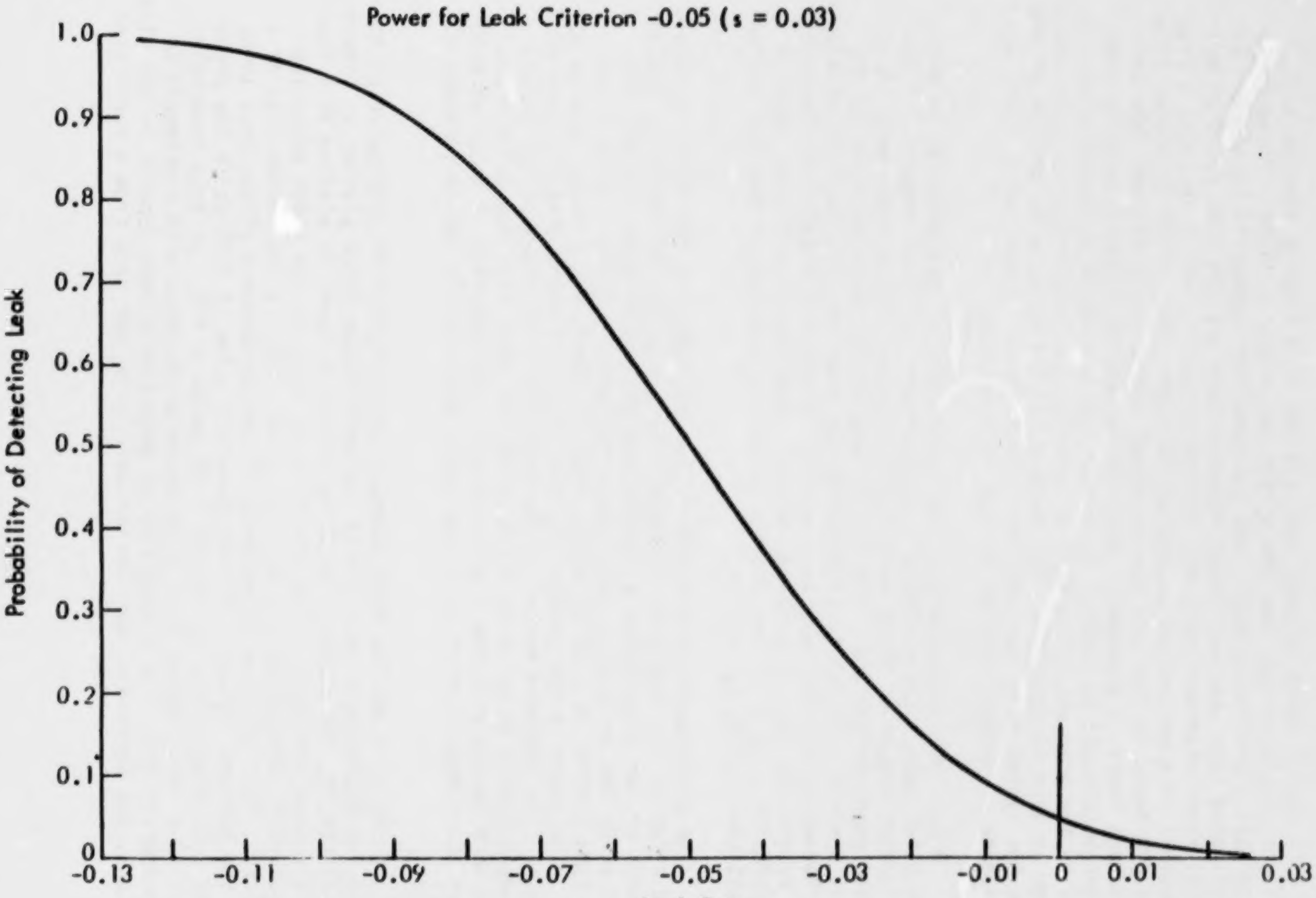

Figure 36. Performance curve.

VI. RECOMMENDATIONS FOR NATIONAL SURVEY

The modified Petro-Tite test method, as refined based on the pilot study, should be used for the national survey. The key modifications include:

- Temperature and volume measurements should be made at 5-min intervals.
- The test period should provide data for not less than 2 h.
- The volume and temperature data should be plotted to indicate trends and provide visual diagnostic checks.
- The results should be analyzed using smoothing techniques for the temperature data.
- The data analysis should provide standard error estimates as well as leak rates and be flexible enough to accommodate unusual trends such as curvilinearity and non-monotonicity.

These recommendations and selection of a modified Petro-Tite method for the national survey do not constitute an endorsement of a tank test method by the U.S. Environmental Protection Agency.

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APPENDIX A

DEFINITION OF TERMS

The following terms are defined as used in this report.

Accuracy - Degree to which a measurement process duplicates a known true value.

Backfill - Material used to fill in around tanks. Usually consists of pea gravel or sand.

Bias - A systematic error common to all measurements made with a particular device. The average difference between a series of measurements and the true value. A measure of accuracy.

Bung - Plug used to close extra openings in top of tank.

Dispenser - Unit containing meter and valves for filling vehicles with fuel.

Distribution line - Piping which delivers fuel to other locations such as dispensers or other tanks.

Drop tube - Tube that extends from fill pipe to near bottom of tank. Permanent drop tubes cannot be removed without modifications to the tank. Removable drop tubes can be easily removed for testing purposes.

Fill pipe - Opening into tank through which fuel is added to the tank. Remote fill pipes do not lead directly into the tank and are usually located some distance from the tank.

Foot valve - A check valve used to prevent fuel from flowing backwards through a line.

Fuel - Also called "product". See Appendix B for descriptions of fuel types.

Manifold system - Two or more tanks connected together such that fuel flows between them when added or removed from either tank. The term is also used in inventory analysis to indicate a system where two or more tanks have a common dispenser, regardless of whether fuel flows between them.

Manway - Access port into tank large enough to allow a person to enter the tank.

NFPA recommended standard - The National Fire Protection Association (NFPA) recommends in its Bulletin 329 that "precision testers" be capable of detecting leaks of 0.05 gal/h.

Precision - Degree to which repeated measurements made by the same device under identical conditions vary about a central value.

Pressure pump - Also referred to as a remote or turbine system. The pump supplying the fuel to the dispenser is located in the tank below the product level. Fuel is supplied to the dispenser under pressure.

Root mean squared error - A statistical measure of the variability of an estimate that incorporates both precision and accuracy.

Sensitivity - Degree to which a measurement device is affected by or responds to changes.

Standard deviation - A statistical measure of the precision of a measurement. It is estimated by the following formula:

$$s = \Sigma \frac{(x_i - \bar{x})^2}{n - 1}, \text{ when}$$

$$\bar{x} = \frac{1}{n} \Sigma x_i \text{ is the arithmetic mean}$$

Standard error - A statistical measure of the precision of an estimate. The standard error of the mean is 1/ n times the standard deviation, where n is the number of terms.

Standpipe - An extension added to an access port into the tank for the purpose of bringing the fuel level above grade.

Suction pump - The pump supplying fuel to the dispenser. Located outside the tank. Fuel is drawn into the line under reduced pressure before dispensing.

Tank system - The tank and all ancillary connections such as vent lines, delivery lines, manifolds, and other tanks connected by manifold. The entire system is tested as a complete unit.

Vent pipe - Piping extending from the top of the tank to the atmosphere for the purpose of preventing pressure buildup in the tank.

APPENDIX B

GLOSSARY OF FUELS

I. AVIATION GASOLINE (FINISHED)

All special grades of gasoline for use in aviation reciprocating engines, as given in ASTM Specification D 910 and Military Specification MIL-G-5572. Excludes components used in blending or compounding into finished aviation gasoline. Three grades of aviation gasoline: Grade 80-red, Grade 100-green, and Grade 100LL-blue. Grades 100 and 100LL represent two aviation gasolines that are identical in anti-knock quality but that differ in maximum lead content and color. The color identifies the difference for those engines which have a low tolerance to lead.

II. DISTILLATE FUEL OIL

A general classification for one of the petroleum fractions produced in conventional distillation operations. Used primarily for space heating, on- and off-highway diesel engines (including railroad engines and agricultural machinery), and electric power generation. Included are products known as No. 1, No. 2, and No. 4 fuel oils and No. 1 and No. 2 diesel fuels.

A. No. 1 Distillate

A petroleum distillate which meets the specifications for No. 1 heating or fuel oil as defined in ASTM D 396 and/or the specifications for No. 1 diesel fuel as defined in ASTM D 975.

1. No. 1 Diesel Fuel

A volatile distillate fuel oil having a boiling range between 300° and 375°F and used in high-speed diesel engines generally operated under wide variations in speed and load. Includes type C-B diesel fuel used for city buses and similar operations. Properties are defined in ASTM D 975.

2. No. 1 Fuel Oil

A light distillate fuel oil used in vaporizing pot-type burners. ASTM D 396 specifies for this grade maximum distillation temperatures of 400°F at the 10% point and 550°F at the 90% point, and kinematic viscosities between 1.4 and 2.2 centistokes at 100°F.

B. No. 2 Distillate

A petroleum distillate fuel oil which meets the specifications for No. 2 heating or fuel oil as defined in ASTM D 396 and/or the specifications for No. 2 diesel fuel as defined in ASTM D 975.

1. No. 2 Diesel Fuel

A gas-oil distillate of lower volatility than that of No. 1. diesel oil, with distillation temperatures between 540° and 640°F at the 90% point and used in high-speed diesel engines generally operated under uniform speed and load conditions. Includes type R-R diesel fuel used for railroad locomotive engines, and type T-T diesel fuel used for diesel-engine trucks. No. 2 diesel fuel is also used in agricultural machinery and in marine vehicles. Properties are defined in ASTM Specification D 975.

2. No. 2 Fuel Oil

A distillate fuel oil used in atomizing-type burners for domestic heating or for moderate capacity commercial-industrial burner units. ASTM D 396 specifies for this grade distillation temperatures between 540° and 640°F at the 90% point and kinematic viscosities between 2.0 and 3.6 centistokes at 100°F.

C. No. 4 Distillate

A fuel oil used for commercial burner installations that are not equipped with preheating facilities. It is used extensively in industrial plants. This grade is a blend of distillate fuel oil and residual fuel oil stocks that conforms to ASTM Specification D 396 or Federal Specification VV-F-815C; its kinematic viscosity is between 5.8 and 26.4 centistokes at 100°F.

III. KEROSENE

A petroleum distillate that boils at a temperature between 300° and 500°F, that has a flashpoint higher than 100°F by ASTM Method D 56, that has a gravity range from 40° to 46° API, and that has a burning point in the range of 150° to 175°F. Included are the two classifications recognized by ASTM Specification D 3699 (No. 1-K and No. 2-K) and all grades of kerosene called range or stove oil that have properties similar to No. 1 fuel oil, but with a gravity of about 43° API and a maximum end point of 625°F. Kerosene is used in space heaters, cookstoves, and water heaters and is suitable for use as an illuminant when burned in wick lamps.

IV. KEROSENE-TYPE JET FUEL

A quality kerosene product with an average gravity of 40.7° API, and a 10% distillation temperature of 400°F. It is covered by ASTM Specification D 1655 and Military Specification MIL-T-5624L (Grades JP-5 and JP-8). Three types of aviation turbine fuel are Jet A, Jet A-1, and Jet B. Jet A and Jet A-1 are relatively high flashpoint distillates of the kerosene type but with differing freezing points. Jet B is a relatively wide boiling range volatile distillate. A relatively low freezing point distillate of the kerosene type, it is used primarily for commercial turbojet and turboprop aircraft engines.

V. LIQUIFIED PETROLEUM GASES

Ethane, ethylene, propane, propylene, normal butane, butylene, and isobutane produced at refineries or natural gas processing plants, including plants that fractionate raw natural gas plant liquids.

VI. MOTOR GASOLINE (FINISHED)

A complex mixture of relatively volatile hydrocarbons, with or without small quantities of additives, that have been blended to form a fuel suitable for use in spark-ignition internal combustion engines used in automotive, marine, and stationary equipment. Specifications for motor gasoline, as given in ASTM Specification D 439 or Federal Specification VV-G-1690C, include boiling temperatures of 122° to 158°F at the 10% point and 365° to 374°F at the 90% point, and a Reid vapor pressure range from 9 to 15 psi. Motor gasoline or "Mogas," includes finished leaded gasoline, finished unleaded gasoline, and gasohol. Blendstock is excluded until blending has been completed. (Alcohol that is to be used in the blending of gasohol is also excluded.)

A. Regular Gasoline

As defined in ASTM D 439 and Environmental Protection Agency (EPA) specifications, gasoline anti-knock designation equal to or less than 3. Includes both leaded and unleaded regular gasoline. Excludes any blendstock until blending has been completed and the blendstock is incorporated in the finished leaded gasoline and no longer separately identified.

1. Leaded Regular Gasoline

As defined in ASTM D 439 and EPA specifications, gasoline anti-knock designation 3 produced with the use of any lead additives or which contain more than 0.05 g of lead per gallon or more than 0.005 g of phosphorus.

2. Unleaded Regular Gasoline

As defined in ASTM D 439 and EPA specifications, gasoline anti-knock designation 2 containing not more than 0.05 g of lead per gallon and not more than 0.005 g of phosphorus.

B. Premium Gasoline

As defined in ASTM D 439 and EPA specifications, gasoline anti-knock designation ≦ 4. Includes both leaded and unleaded premium gasoline. Also includes the entire volume of gasohol, both the gasoline and the alcohol.

1. Leaded Premium Gasoline

As defined in ASTM D 439 and EPA specifications, gasoline anti-knock designation 5 produced with the use of any lead additives or which contains more than 0.05 g of lead per gallon or more than 0.005 g of phosphorus.

2. Unleaded Premium Gasoline

As defined in ASTM D 439 and EPA specifications, gasoline anti-knock designation 4 containing not more than 0.05 g of lead per gallon and not more than 0.005 g of phosphorus.

3. Gasohol

A blend of finished motor gasoline (leaded or unleaded) and alcohol (generally ethanol but sometimes methanol) in which 10% or more of the product is alcohol.

VII. NAPHTHA-TYPE JET FUEL

A fuel in the heavy naphtha boiling range with an average gravity of 52.8° API and 20 to 90% distillation temperatures of 290° to 470°F, meeting Military Specification MIL-T-5624L (Grade JP-4). JP-4 is used for turbojet and turboprop aircraft engines, primarily by the military. This category excludes ram-jet and petroleum rocket fuels, which are included in the "Miscellaneous Products" category.

VIII. PROPANE, CONSUMER GRADE

A normally gaseous parafinic compound (C_3H_8), which includes all products covered by Natural Gas Policy Act (NGPA) specifications for commercial use and HD-5 propane and ASTM Specification D 1835. Excludes feedstock propanes, which are propanes not classified as consumer grade propanes, including the propane portion of any natural gas liquids mixes, i.e., butane-propane mix.

IX. RESIDUAL FUEL OILS

The topped crude of refinery operations, which includes No. 5 and No. 6 fuel oils as defined in ASTM Specification D 396, Navy Special fuel oil (NSFO) as defined in Military Specification MIL-F-859E including Amendment 2 (NATO symbol F-77), and Bunker C fuel oil. Residual fuel oil is used for the production of electric power, space heating, vessel bunkering, and various industrial purposes.

Table B-1. Petroleum Products Included in National Survey of Underground Storage Tanks

Type	Uses	Occurrence
Aviation gasoline (finished)	Reciprocating aircraft engine	Small airports
Distillate fuel oil, diesel fuel		
No. 1	City buses and similar vehicles	Bus stations
No. 2	Diesel cars and trucks, marine crafts, railroad locomotives, farm machinery, military tanks	Truckstops, railyards, military
Kerosene-type jet fuel	Commercial turbojet and turboprop aircraft engine	Small airports, large airports
Motor gasoline (finished)	Automobiles, light trucks, motorcycles, various machinery and equipment	Service stations, convenience stores, farms, fleets
Naphtha-type jet fuel	Military turbojet and turboprop aircraft engine	Military facilities

Table B-2. Petroleum Products Not Included in National Survey of Underground Storage Tanks

Type	Uses	Occurrence
Distillate fuel oils No. 1, 2, and 4	Heating	Industry, homes
Kerosene	Space heaters, water heaters, cookstoves	Homes
Liquified petroleum gases	Domestic, commercial, and industry fuels, and refinery, and petrochemical raw materials	Homes, industry, commercial
Propane, consumer grade	Heating	Homes, industry
Residual fuel oils	Industrial purposes, space heating	Industry

Table B-3. Volumetric Coefficients of Expansion and Average Densities of Fuels Selected for National Survey of Underground Storage Tanks

Fuel	VCE	Density (g/cm^3)
Aviation gasoline	.00056	NA[a]
Diesel fuel	.0004	NA
Kerosene-type jet fuel	NA	.82
Motor gasoline	.00068	.66-.69
Leaded regular		
Unleaded regular		
Premium		
Gasohol		
Ethyl alcohol	.00062	.791
Methyl alcohol	.00072	.810
Naphtha-type jet fuel	NA	.665

[a] NA = not available.

APPENDIX C

SOURCES OF ERROR IN VOLUMETRIC TEST METHODS

This appendix presents the various interfering factors that can influence the results of volumetric tank tests. Although these factors are discussed primarily within the context of the methods evaluated during this study, much of the discussion is also applicable to other volumetric methods. The major sources of influence--factors other than leaks that affect determination of leaks in the tank--discussed in this appendix are temperature, vapor pockets, tank deformations, vibrations, water table, and evaporation and condensation.

In general, volumetric measurements involve monitoring the liquid levels and liquid temperature in a tank over a specific period of time. Changes in the liquid level are corrected for expansion and contraction of the liquid as the result of temperature changes which may have occurred during the testing. The net change in level is converted to equivalent volume, and the leak rate is calculated in terms of volume loss per hour. Differences in the quality of the results are due largely to the ability of the test operator to identify and correct for these sources of error. The success of the method may be more dependent upon operator skill than on the test apparatus in many cases, although in some situations the test method may be selected to eliminate an error source. For example, methods which do not require overfilling the tank eliminate vapor pocket effects in nearly all cases.

A. Temperature

Temperature is the single most important source of error in tank testing. Failure to adequately measure and apply temperature corrections can easily lead to incorrect conclusions (either false positives or false negatives). The magnitude of the temperature effect is illustrated by the fact that an error of only 0.01°F will result in a temperature/volume correction error of approximately 0.06 gal in a 10,000-gal tank. The effect is shown graphically in Figure C-1 for three tank sizes. Figure C-2 depicts three different temperature changes which will produce a volume change of 0.05 gal, 0.10 gal, and 0.20 gal in a range of tank sizes.

Nearly all volumetric methods require determination of the average temperature of the product in the tank. The approach varies widely, but the assumption that the test equipment accurately represents or compensates for the temperature behavior of the tank is the key feature.

One method uses product circulation prior to and during the testing in an attempt to produce a uniform temperature. A single thermistor located near the pump inlet monitors the temperature during the test. Although circulation seems to work well, limited data are available to document performance. If circulation is not complete, significant errors may result. Some data are presented in Appendix D.

Several methods which do not use product circulation use either a single thermistor or multiple thermistors located at various levels below the fill pipe. It is usually desirable to wait until stabilization has occurred after filling before conducting the test. The basic assumption of the single

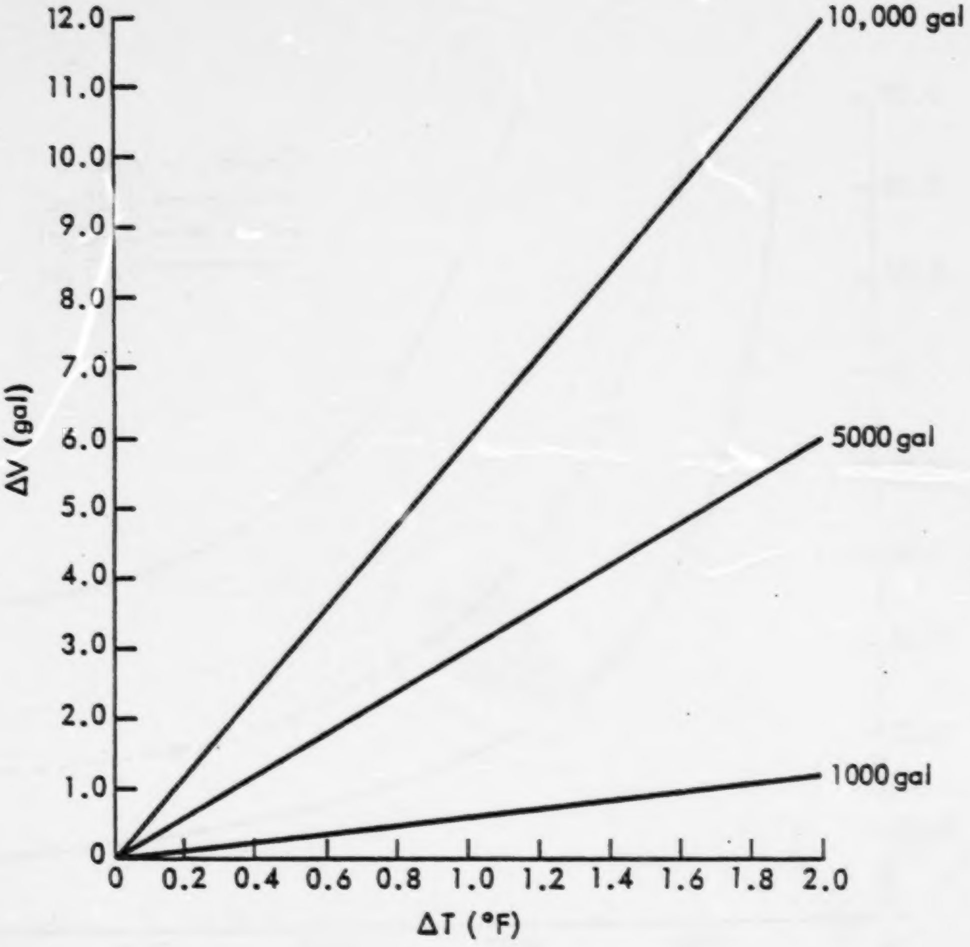


Figure C-1. Change in volume of gasoline as a function of temperature.

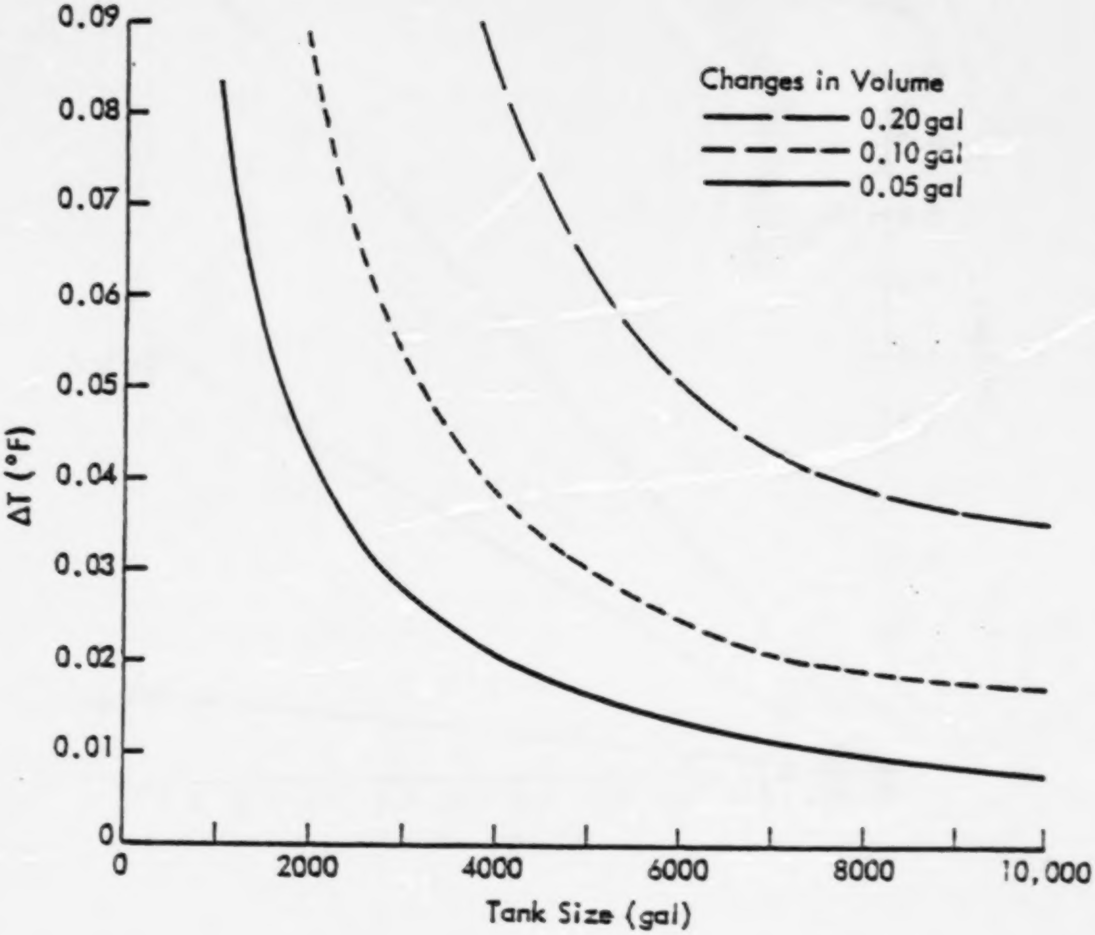


Figure C-2. Change in temperature of gasoline needed to produce a volume change as a function of tank size.

thermistor approach is that if temperature stratification is present, all layers will change at the same rate. If multiple thermistors are used, the volume of the tank represented by each thermistor is used to calculate the temperature behavior of the tank contents. Again, only limited data are available to evaluate the procedure.

A third approach, used only by Arco, is to locate the level sensor float at the point in the tank where changes in level due to temperature are directly compensated by the change in fuel density, or buoyancy. The net result is temperature self-compensation. Placement of the float is dependent on the tank geometry and may not be obvious. Even though this method is self-compensating, it still assumes that there is uniform temperature behavior in the tank.

Unstable temperature behavior can often be detected by properly trained test crews. Corrections can then be applied by providing additional stabilization time, additional mixing, or by adding more temperature sensors. Failure to detect problems with temperature measurements generally results in erroneous conclusions.

There are two additional sources of temperature variability which may contribute to uncertainty in the test results. First, many of the test methods fill up the tank the night before but add several gallons (topping off) immediately before starting the test the next day to raise the level into the fill tube or above grade. If the test is begun immediately after topping the tank with product that is at a different temperature, as it usually is, then the thermistor array will locally measure the changes in temperature of the added product as it mixes in the vicinity of the fill tube and thermistor array. This effect may last several hours and the temperature changes will not be indicative of the average temperature change in the tank. Second, periodic temperature fluctuations occur in the tank which are caused by interval waves. The period and amplitude of these waves depend on the tank geometry and density (temperature) profile. The waves typically form at the boundary of two different fluids of different densities. This is a problem if only one or two thermistors are being used to measure temperature fluctuations or if the data are undersampled.

B. Vapor Pockets

Vapor pockets are a result of air or vapor trapped in the tank when overfilling is complete. These may be due to a tilted tank, manways, air in plumbing associated with the tank, or other tank configurations. They can be a large source of error for two reasons. First, since the expansion coefficient for gases or vapors is much larger than for liquids, changes in temperatures will produce proportionally larger changes in volume. If the pocket remains trapped, the change in vapor volume will be measured as a change in liquid volume. This is shown graphically in Figure C-3.

Second, changes in pressure can affect volume substantially. This would be a problem only if a severe change in atmospheric conditions occurred during the test time. The magnitude of this effect is shown in Figure C-4. As can be seen, unless the vapor pocket is large (100 gal), the effect of small pressure changes is small; but it could in some instances be significant.

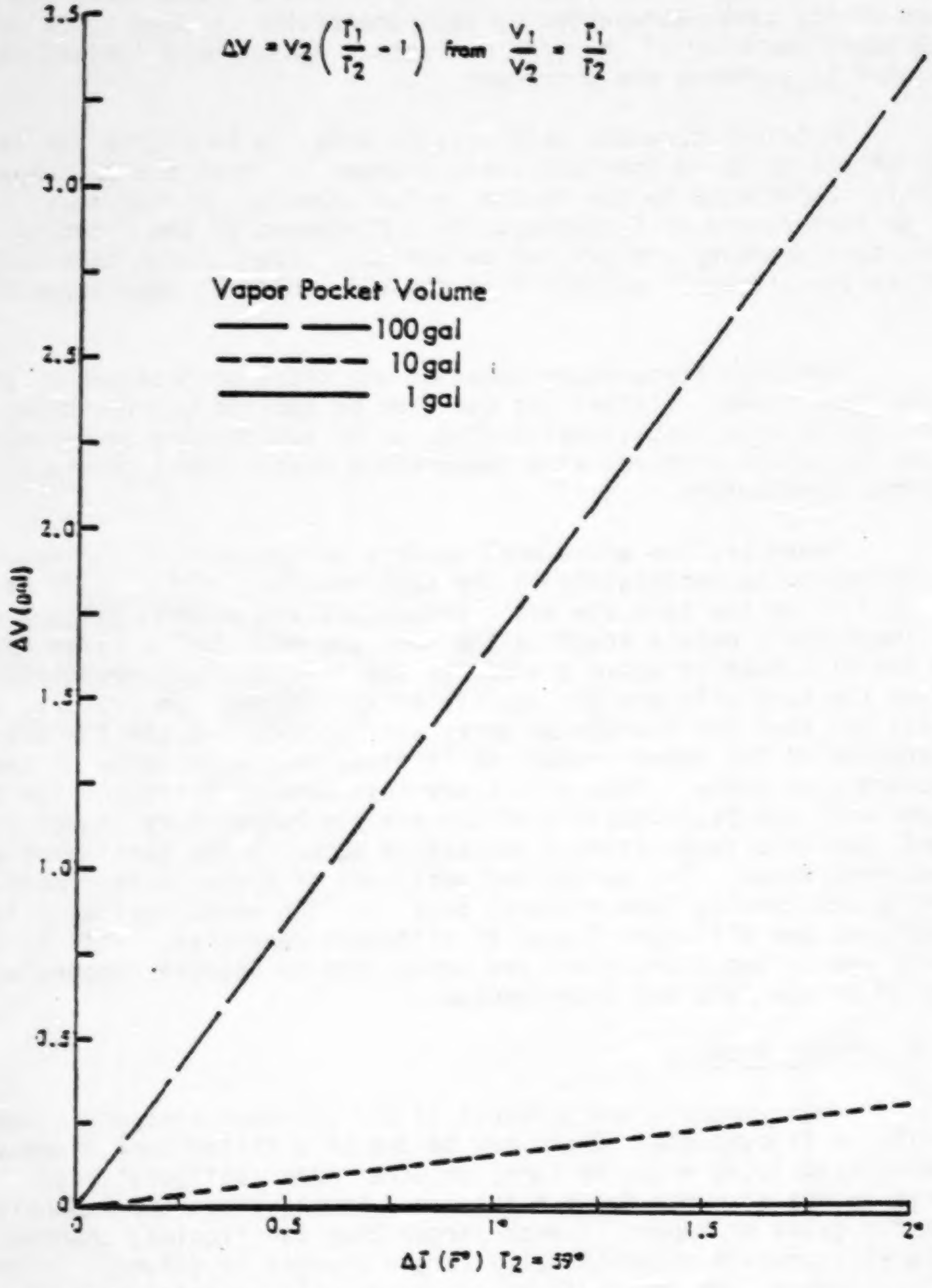


Figure C-3. Changes in measured product volume as a function of changes in temperature at 59°F for three vapor pocket volumes.

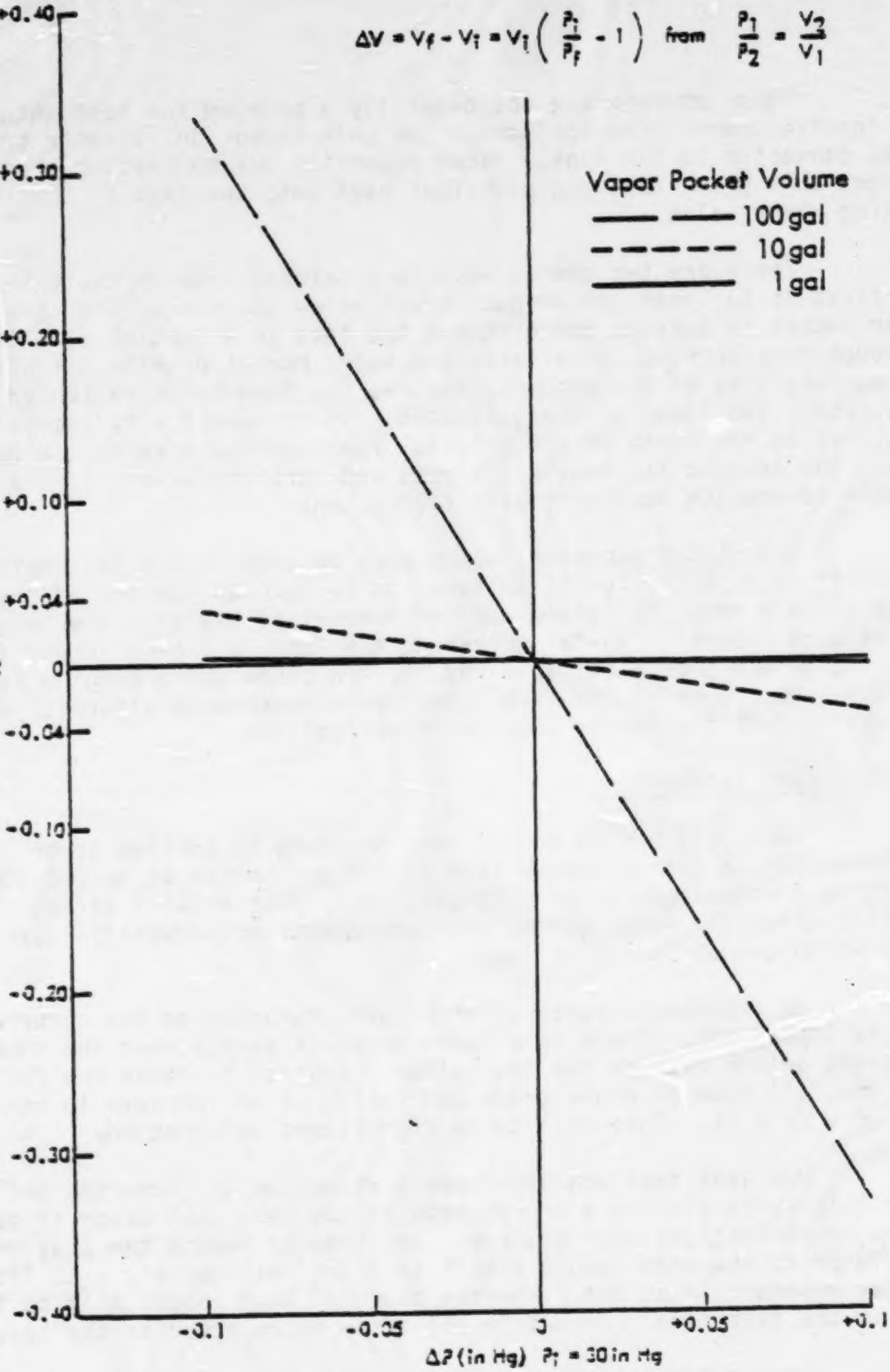


Figure C-4. Changes in product volume as a function of pressure changes for three vapor pocket volumes.

Vapor pockets are not generally a problem for test methods which do not involve overfilling the tank. The only exception is vapor trapped in lines connected to the tank. Vapor expansion due to heating or pressure changes during the test can push fuel back into the tank if the line has a leaking check valve.

There are two common ways to eliminate vapor pockets in the tank. The first is to lower the product level below the top of the tank until the vapor pocket is exposed and continue the test in a partially filled tank. Although this approach eliminates the vapor pocket problem, it also increases the surface area of the product, reduces the head pressure (which reduces the leak rate), and leads to a significant loss in sensitivity approximately proportional to the ratio of the original fuel surface area to the new surface area. The process is, however, simple and straightforward if the test method is able to operate on a partially filled tank.

The second approach, which must be used if the test method is not adaptable to a partially filled tank, is to uncover the top of the tank and bleed the air from the system. After removal of the air, the tank is retested in the usual manner. While uncovering the tank is expensive and invasive, it does facilitate a more reliable result. In cases where digging is impractical or expensive, lowering the level provides a reasonable alternative which can at least detect the larger leaks with reliability.

C. Tank Deformation

Tank deformation occurs when pressure is applied to or removed fr the tank. On an 8-ft diameter tank an end deflection of only 0.0048 in. wil result in a volume change of 0.05 gal. Many factors will affect this process. Backfill material, water table, and tank construction material are all variables which cannot be controlled.

An important source of structural deformation may occur when the tank is topped off. There is a false sense of safety when the tank is filled the night before because the few gallons required to raise the full level into the fill tube or above grade can easily be an increase in the pressure head of 2 to 6 ft. This will cause significant deformation.

One leak test approach uses a standpipe to force the deflections to occur quickly by placing a 5-psig head on the tank just prior to testing until the major deflections have occurred, and then to reduce the pressure to 4 psig. At this point the ends should stabilize relatively quickly with little or no further movement in or out. Another commonly used approach is to fill the tank to the test level (or nearly so) a few hours prior to the test.

Tank deformation can sometimes be recognized from a decreasing observed leak rate over a period of time as the rate asymptotically approaches a stable configuration. Currently there is no simple, reliable way to determine if end deflection has stabilized except to wait for a period of time based on experience and test method. If outward end deflection is occurring during the test, the result will be to enhance an existing leak or to produce an apparent leak in a tight tank. Some data collected during the pilot study which indicated that the relaxation times ranged from 8 to 40 min.

D. Vibration

Large vibrations produce waves on the surface of the product which can make accurate reading of the level difficult. The effect is most severe for methods that rely on measuring very small level changes. Vibrations can occur as a result of nearby traffic or windy conditions. It is usually possible to extend test times, delay testing, or remove the vibration source to obtain valid test results.

E. Water Table

The presence of a water table will decrease the observed leak rate by reducing the differential pressure in the tank and by increasing the resistance to liquid flow. If the fuel head is balanced exactly by the water table head, no flow will be observed no matter how large the hole. If the hydrostatic head is higher than the fuel head, water will flow into the tank producing an increase in product level during the testing.

Some methods, such as that of Petro-Tite, attempt to compensate for water table effects by raising the fuel head so that the differential pressure on the tank bottom remains constant for all tests. This ensures that fuel will flow out of the tank rather than water flowing in during testing. It may also lead to misleading conclusions since holes above the water table will be affected differently from holes below. In addition, a bore hole must be installed at each site to accurately determine the water table level. This can be costly and/or inconvenient.

The exact effects of a water table cannot be calculated readily unless the position and size of holes in the tank are known. The means to achieve accurate evaluation were beyond the scope of this project; however, generalizations can be made based on Bernoulli's principle. This is represented graphically in Figure C-5 for two sizes of holes. The behavior is represented mathematically by the equation

$$\frac{r_1}{r_2} = \sqrt{\frac{h_1}{h_2}}$$

where r_1 and r_2 are the rates at a given hole for two different head pressures h_1 and h_2. Tables C-1 and C-2 illustrate the differential pressure for various water table levels under testing and operating conditions.

F. Evaporation and Condensation

Product loss due to evaporation is a potential problem, particularly during hot or windy conditions where the tank is partially filled. If the test system is tight, no loss will occur. Evaporation of product from the standpipe could occur if the cover were left open during testing. Condensation is generally a problem only if water condenses on the walls of the fill

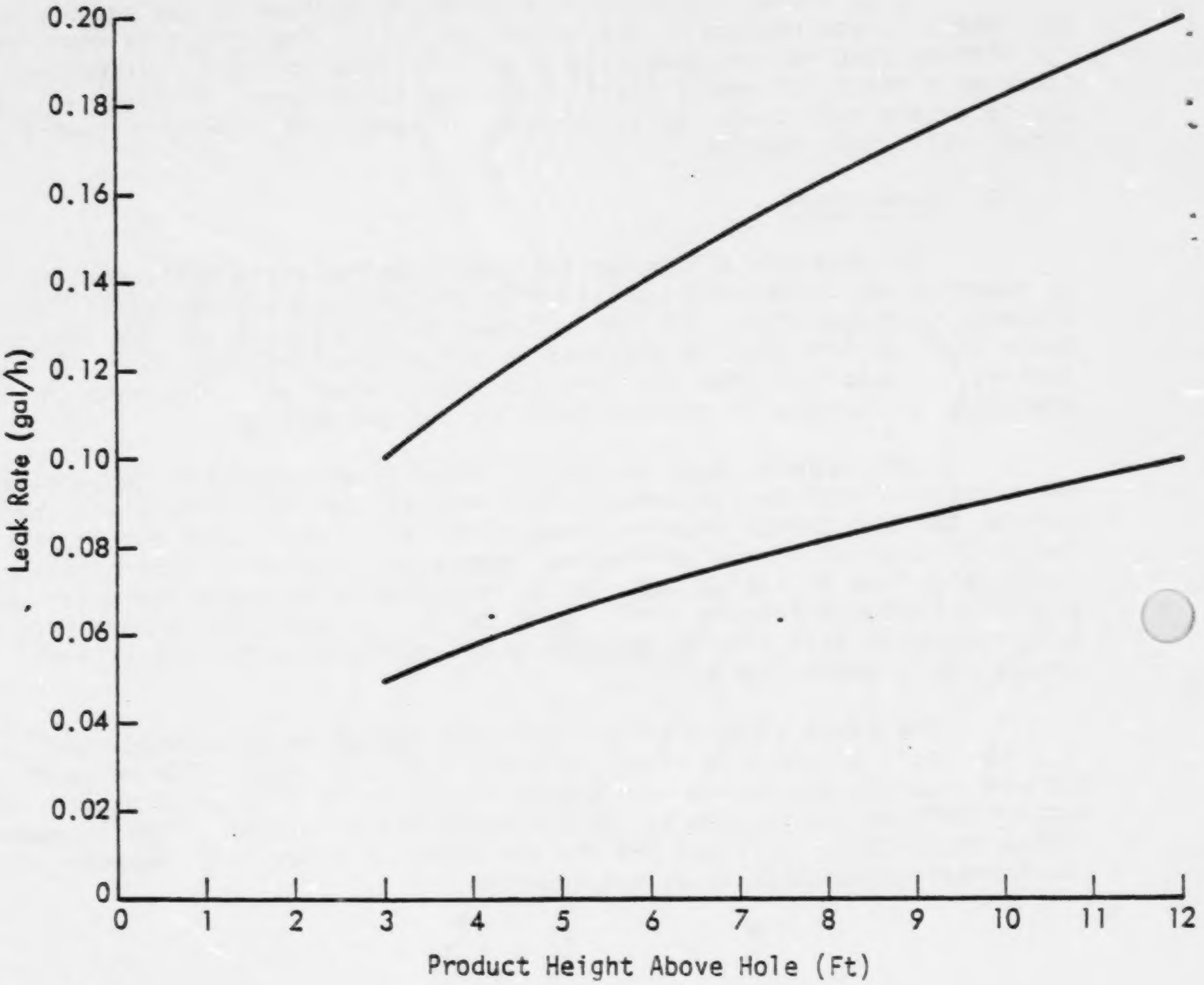


Figure C-5. Change in observed leak rate as a function of head pressure (feet of fuel) above the hole.

Table C-1. Differential Pressure (psig) Where Fuel Head is Adjusted to Product 4.00 lb of Pressure at Tank Bottom for Various Water Table Levels During Testing

	Water table level			
Distance below grade	Below tank	Mid level	Tank top	Surface
0 ft (surface)	0.56	2.30	4.02	5.30
3 ft (top)	1.50	3.23	4.96	4.96
7 ft (mid level)	2.75	4.48	4.48	4.48
11 ft (bottom)	4.00	4.00	4.00	4.00

Table C-2. Differential Pressure (psig) of Gasoline Head for Various Water Table Levels Under Operating Conditions

	Water table level			
Fraction filled	Below tank	Mid level	Tank top	Surface
Surface (11 ft)	3.43	1.7	-0.03	-1.32
Full (8 ft)	2.50	0.77	-0.96	-2.25
3/4 (6 ft)	1.87	0.14	-1.59	-2.88
1/2 (4 ft)	1.25	-0.48	-2.21	-3.50
1/4 (2 ft)	0.64	-1.09	-2.82	-4.11

pipe and drains into the tank. One buoyancy method compensates for this effect by having product placed in a cup which is part of the sensor mechanism. Evaporation losses from the fill pipe are compensated automatically by evaporation losses from the cup.

APPENDIX D

TEMPERATURE BEHAVIOR STUDIES

I. INTRODUCTION AND BACKGROUND

The precision and accuracy of leak detection methods are largely dependent upon their ability to recognize significant sources of variability and to compensate for them accordingly. The primary physical properties of gasoline, related hydrocarbons, and fuels warrant considering temperature as one of the key parameters. The approach taken for temperature compensation for most methods assumes that the temperature changes throughout the tank are uniform. Although some data can be found to support these assumptions, other data suggest that there are situations where they may not be valid.

Product level changes encountered during testing may be partially attributed to the contraction and/or expansion of the product being tested due to temperature changes of the product. Because these temperature effects can be pronounced, they must be accurately measured and appropriate corrections applied to the data.

The basic approach taken is to measure the temperature of the product using a thermistor (or thermistors) located in the tank. The observed temperature change is then used to calculate a volume change, which is then added to (in the case of decreasing temperature) or subtracted from (in the case of increasing temperature) the volume changes observed during the test to obtain a corrected leak rate.

This appendix summarizes the observations of several types of temperature studies conducted by MRI from various sources during the development and pilot programs. The information was used to characterize the performance of the methods evaluated during the method development study as well as to assess the impact of temperature uncertainties on the test data.

During the development study, three types of temperature data were obtained.

1. Vertical temperature profiles of each tank tested during the development study were measured at the beginning and end of each test.

2. A study that monitored temperature changes over an extended time period was designed and conducted by MRI and Vista Research, Inc.

3. Temperature data from two Petro-Tite tests were obtained to assess completeness of mixing.

These data were used to supplement the characterization and evaluations of the temperature compensation procedures which were evaluated. Each type of data is discussed separately below.

II. TEMPERATURE PROFILES

A. Experimental Approach

Vertical temperature profiles were obtained at each tank by lowering a single thermistor into the tank in 6-in. intervals. The thermistor was allowed to stabilize at each interval until the digital readout showed random fluctuations only in the hundredths range (usually this was 30 s to 1 min at each level). The thermistor was then moved to the next level and the process repeated. Temperatures were recorded manually on data forms prepared for that purpose.

When the thermistor reached the bottom of the tank, it was raised to the top in 6-in. increments and the temperatures were again recorded. The cycle (down/up) was typically repeated several times before the testing began and again at the completion of the test.

B. Instrumentation

The instrument used to collect the profile data was a single thermistor attached to an approximately 20-ft cable. The thermistor was connected to a single channel digital readout which displayed temperatures to 0.01°F.

C. Data Analysis

All of the readings obtained for a given series of measurements were averaged for each level. An estimate of the standard deviation was also obtained for series where more than one cycle of data was available. The averaged values were plotted against depth in the tank and a smoothed curve was drawn through the data points.

D. Results

Several examples of profiles obtained on the development study are shown in Figures D-1 through D-4. Data for each plot are also provided in Tables D-1 through D-4. The data were chosen to be representative of different types of behavior and are not intended to imply a frequency of occurrence.

Figure D-1 is an example of a tank with a well behaved temperature profile. Because there is essentially no temperature gradient in the tank, placement of the thermistor is not critical as long as it is not too near the top or bottom of the tank. Calculated temperature corrections should be very representative of the total tank behavior.

Figure D-2 illustrates a less well-behaved system in that a vertical temperature gradient does exist. The temperature shifts along the gradient are not uniform, although neither the shifts nor the differences are large. Considering that the two profiles were conducted approximately 8 h apart, the differences are not surprising.

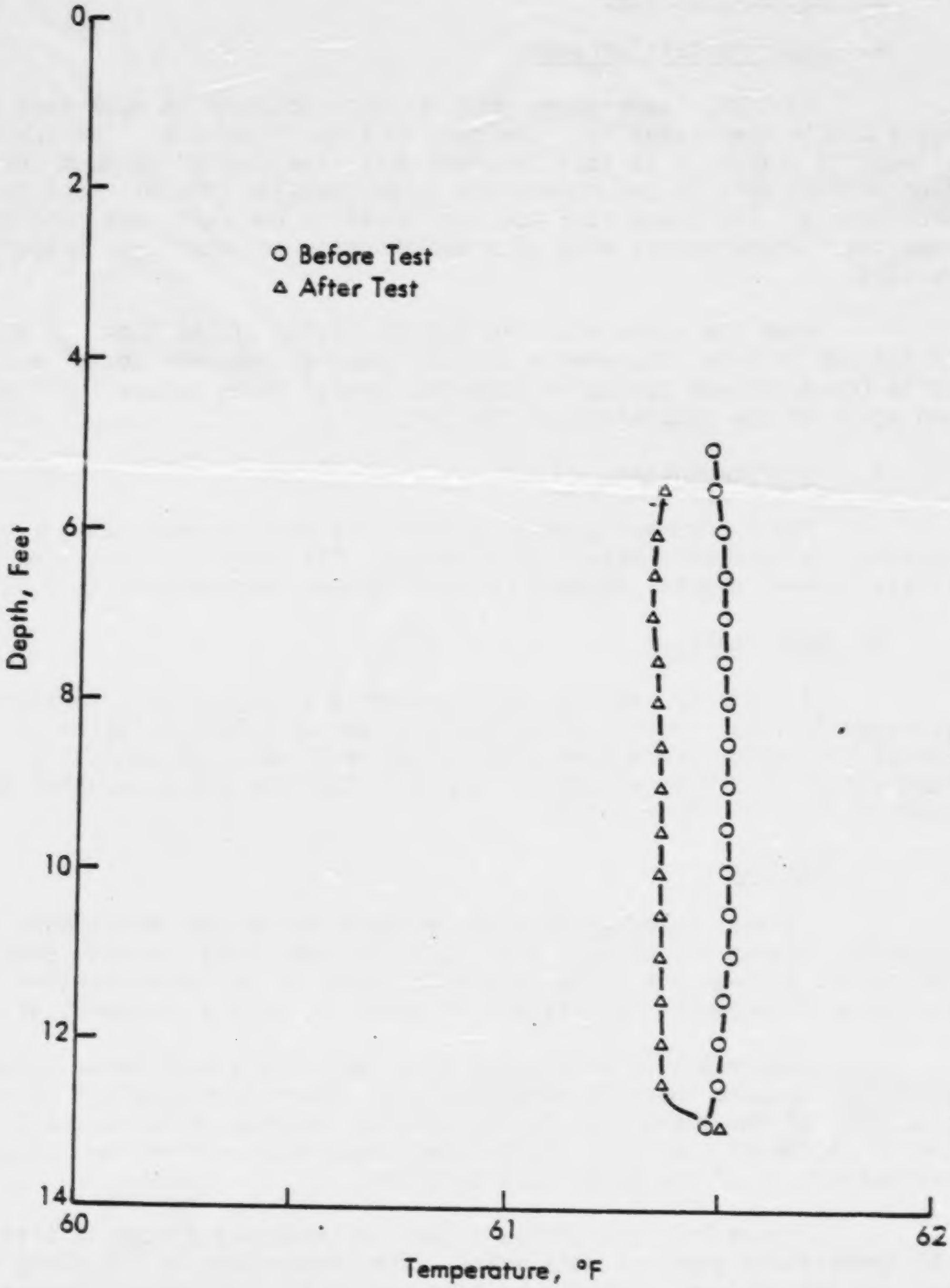


Figure D-1. Temperature changes in unstirred tank--example of uniform temperature shift - Tank A.

Table D-1. Temperature Comparison in an Unstirred Tank, Tank A

Depth (ft)	Mean Temperature (°F)	
	Before test	After test
5	61.47	62.16
5.5	61.49	61.35
6	61.49	61.33
6.5	61.50	61.33
7	61.50	61.33
7.5	61.50	61.34
8	61.51	61.34
8.5	61.51	61.35
9	61.51	61.35
9.5	61.51	61.35
10	61.52	61.35
10.5	61.52	61.35
11	61.51	61.36
11.5	61.50	61.36
12	61.49	61.36
12.5	61.49	61.36
13	61.47	61.50

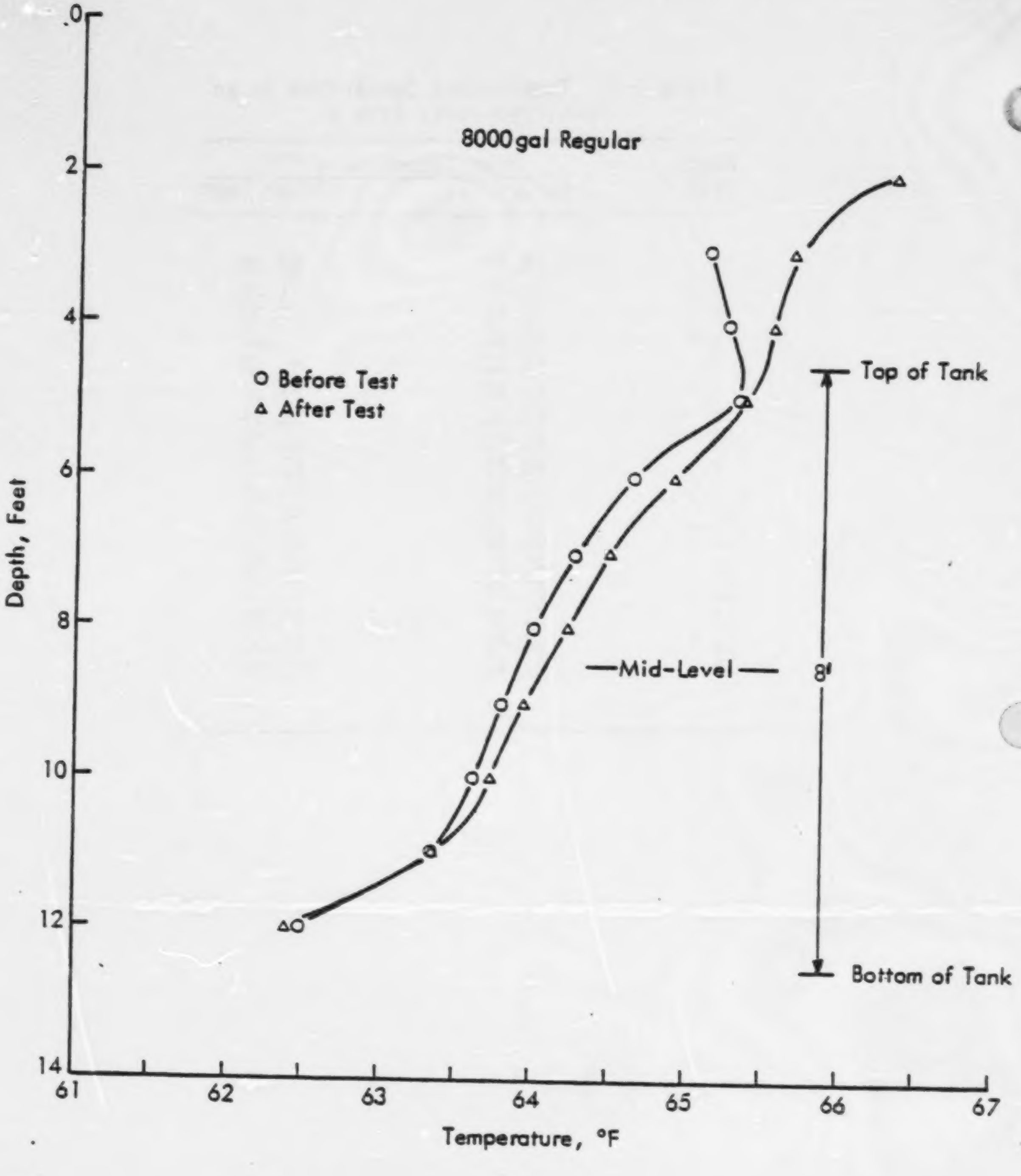


Figure D-2. Temperature changes in unstirred tank--example of nonuniform change - Tank B.

Table D-2. Temperature Comparison in an Unstirred Tank, Tank B

Depth (ft)	Mean temperature (°F) and standard deviation		
	Before test		After test
	Mean temp.	Standard deviation	Mean temp.
3	65.10	0.146	65.63
4	65.24	0.0931	65.50
5	65.31	0.0194	65.38
6	64.62	0.06	64.89
7	64.25	0.0497	64.46
8	63.98	0.0194	64.18
9	63.78	0.0232	63.90
10	63.60	0.0343	63.70
11	63.34	0.0446	63.27
12	62.47	0.0527	62.37

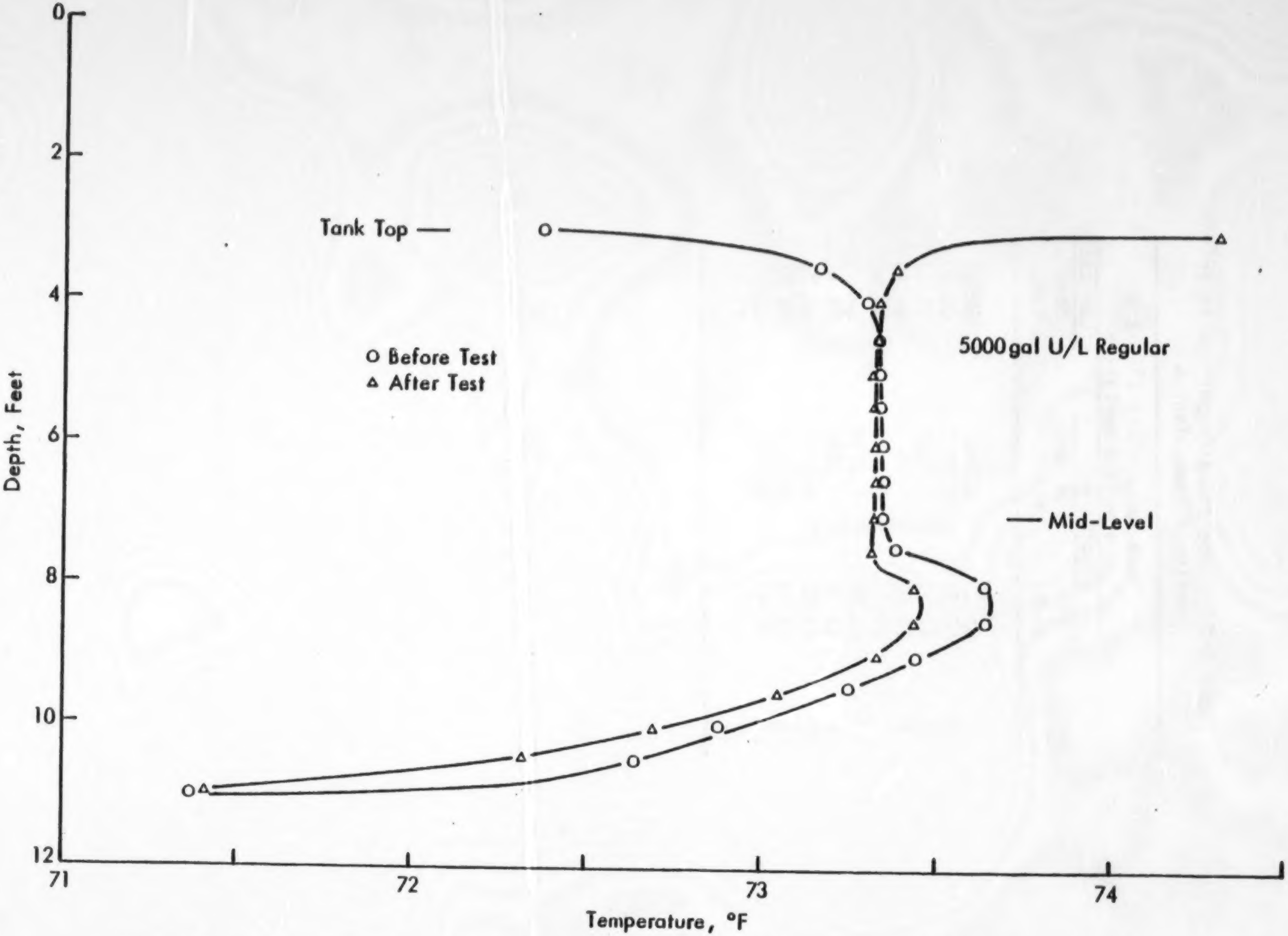


Figure D-3. Temperature change in unstirred tank--example of nonuniform changes - Tank C.

Table D-3. Temperature Comparison in an Unstirred Tank, Tank C

Depth (ft)	Mean temperature (°F)	
	Before test	After test
3	72.73	74.33
3.5	73.16	73.38
4	73.29	73.33
4.5	73.33	73.33
5	73.33	73.32
5.5	73.33	73.32
6	73.33	73.32
6.5	73.33	73.32
7	73.34	73.32
7.5	73.38	73.32
8	73.54	73.44
8.5	73.43	73.44
9	73.44	73.33
9.5	73.25	73.05
10	72.88	72.69
10.5	72.54	72.31
11	71.37	71.40

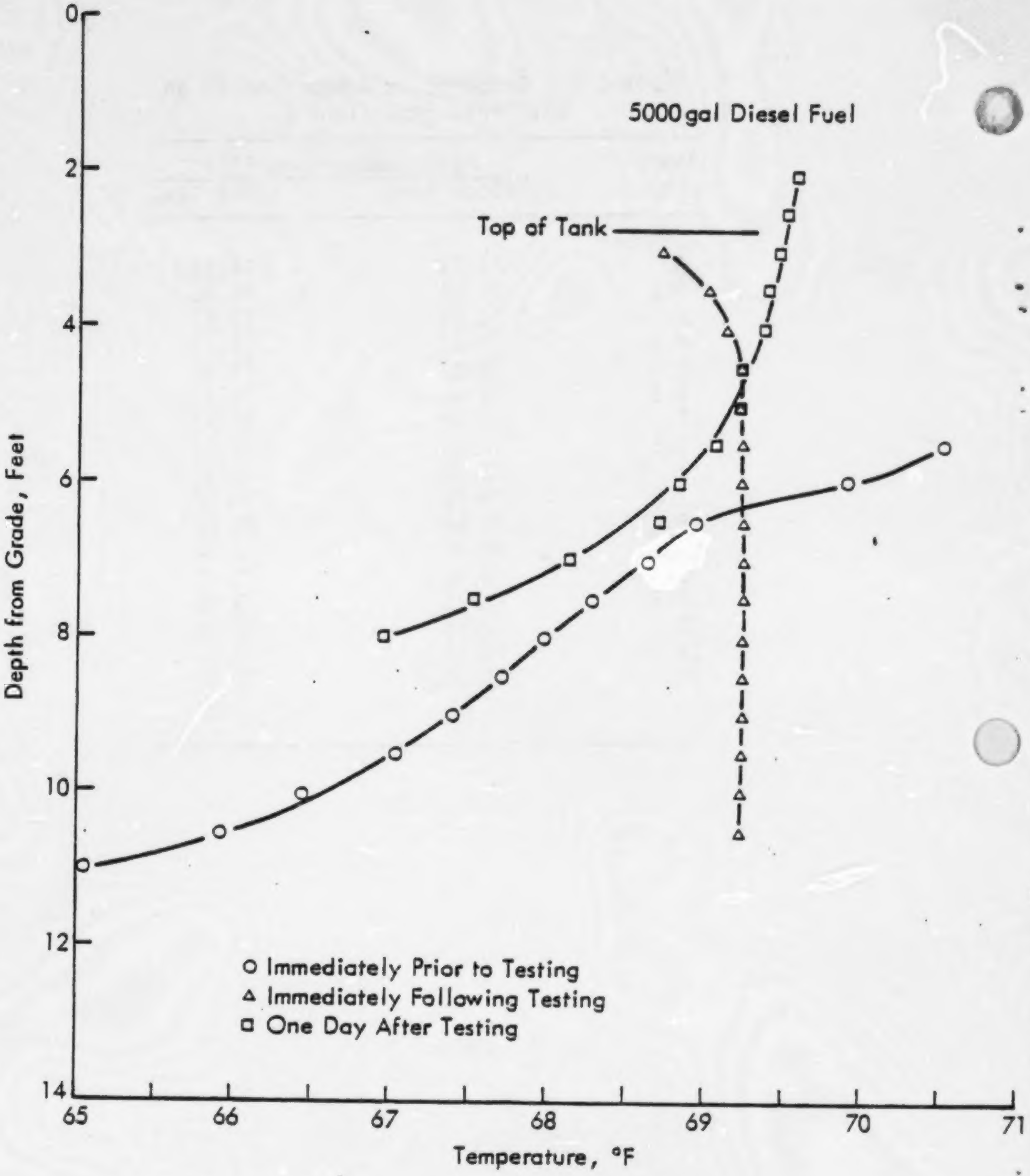


Figure D-4. Temperature changes in Petro-Tite test illustrating temperature behavior in stirred system.

Table D-4. Temperature Comparison in a Stirred Tank, Tank D

Depth (ft)	Mean temperature (°F) and standard deviation					
	Before test		After test		Day following test	
	Mean temp.	Standard deviation	Mean temp.	Standard deviation	Mean temp.	Standard deviation
2					69.54	0.0287
2.5					69.49	0.0427
3			68.70		69.42	0.0386
3.5			69.01	0.272	69.36	0.0419
4			69.17	0.064	69.29	0.0476
4.5			69.21	0.0231	69.23	0.0238
5			69.22	0.0208	69.17	0.0404
5.5	70.50	0.843	69.23	0.0	69.05	0.0337
6	69.85	0.734	69.23	0.00577	68.80	0.154
6.5	68.90	0.757	69.23	0.0	68.46	0.154
7	68.66	0.265	69.24	0.0115	68.12	0.226
7.5	68.27	0.116	69.23	0.0	67.52	0.302
8	67.97	0.161	69.23	0.00577	66.96	0.223
8.5	67.68	0.169	69.24	0.0		
9	67.38	0.233	69.23	0.0		
9.5	67.03	0.254	69.23	0.01		
10	66.48	0.245	69.23	0.0231		
10.5	65.89	0.281	69.22	0.00577		
11	65.01	0.146				

Consider the effect of placing a single thermistor in the center of the tank versus placing three thermistors at the midpoints of one-third volume segments of the tank. The single center thermistor located at the midpoint of the tank exhibits a temperature shift of ± 0.11°F over the 8-h period. This leads to a temperature compensation volume of 0.55 gal total or a volume of 0.07 gal/h.

For the three-thermistor approach one thermistor is placed at the center of each one-third volume segment so that each thermistor represents one-third of the tank's total volume. For an 8-ft tank this places the thermistors at approximately 1.5, 4, and 6.5 ft from the top. Using the temperature changes at these locations from Figure D-2 gives a weighted average of 0.51 gal total or 0.06 gal/h. The differences in this case are negligible.

Figure D-3 presents a set of data which exhibits unstable stratification in the tank. In this case the placement of the thermistor is important. The midpoint and top levels of the tank exhibited almost no temperature shift while at the bottom a considerable shift was observed. If the same calculations are performed for this case as were calculated for Figure D-2, the result is a temperature compensation volume of -0.063 gal or -0.008 gal/h for a single midpoint thermistor and -0.23 gal or -0.03 gal/h for three thermistors. In this case, location of a single thermistor could be critical. Placement of the thermistor 12 in. lower would have produced a dramatic difference. In this case, the temperature change observed would have been 0.1°F, corresponding to a value decrease of -0.315 gal or -0.039 gal/h. The difference between this and the -0.063 gal (-0.008 gal/h) observed at midpoint is substantial.

Figure D-4 shows the behavior of a tank which was tested using the Petro-Tite method. Profiles were obtained before and immediately after the testing. A third profile was obtained approximately one day following the testing. The data are presented in Table D-4.

As can be seen, the stirring action did provide a nearly uniform temperature profile by the end of the test period. The tank tended to return to its original profile when left to stabilize again.

E. Discussion

Although the temperature profiles obtained from this test are informative, discussion of the data must consider the following.

1. The profiles were obtained at only one position in the tank, which was usually close to one end. The temperature behavior in other locations is only inferred to be similar in behavior.

2. The test periods generally extended at least two to four times the duration of typical tank tests. The data collected during a routine test are usually on the order of 1 h.

3. All of the testing took place in September and October when ambient temperature conditions were generally mild. Extremes of either hot or cold weather were not encountered.

4. All tanks were filled at least 12 h before the testing was conducted.

Under the test conditions encountered on this program, the temperature data from unstirred tanks are reasonably well represented by a single thermistor located at the center of the tank. The data represented in Figure D-1 is typical of that frequently encountered. However, the limited data presented in Figures D-2 and D-3 suggest that under some conditions the temperature behavior may be nonuniform. This raises some concerns as to the frequency and severity of the problem which are not answered by the profile data. The major questions are:

1. What is the minimum stabilization time for an unstirred system?

2. Are there significant effects from filling the tank with product which is much warmer or much cooler than the ground temperature around the tank?

3. What effect is produced by topping off the tank with product which is either much warmer or much cooler than that already in the tank?

4. Does ambient temperature affect the test in any way?

5. What is the temperature behavior of tank systems over a long period of time under a variety of conditions?

The behavior of the vertical profiles of the stirred tanks as illustrated in Figure D-4 was typical of all of the Petro-Tite tests. However, it is not known if horizontal mixing is complete as well. This is of some concern because in most cases the profiles were obtained near the pump location, which was usually at one end of the tank. The deflection angle of the nozzle and the implied mixing pattern seem to avoid this problem.

In addition, it is not known when the vertical profiles were brought to a uniform condition. These tests were conducted over an extended time period of 6 t 8 h while the normal Petro-Tite test used data collected after 1 to 2 h of mixing.

As a result of these observations, additional testing was proposed. This is described in Section III.

III. TEMPERATURE STABILITY STUDY

A. Experimental Approach

A temperature stability study was conducted in Kansas City on a 10,000-gal tank located at a temporarily closed service station. The testing involved collecting the following three sets of data:

1. Background temperature behavior of the 4,000 gal of fuel in the tank before the testing and immediately after the filling of the tank.

2. Product temperature over the next few hours without circulation.

3. Product temperature during mixing using a Petro-Tite circulation pump.

The data collected were used to estimate the stabilization time required for testing procedures which do not circulate product and the circulation time required to achieve complete mixing in the tank. As is discussed in the results section, due to the circumstances of the test (fuel temperatures, ground temperature, and ambient temperature), very little temperature gradient resulted from the filling operation. In addition, the electronic components for one of the thermistor arrays were apparently affected by ambient temperature changes. Hence, the temperature change data for that array are suspect.

B. Instrumentation

1. Thermistor Array

To accurately study temperature stratification and gradients for extended periods of time, a rigid support system was utilized to ensure accurate and systematic thermistor placement. The array sytem was designed with an unfolding mechanical arm extending from the vertical support frame, thus enabling the collection of both horizontal and vertical temperature data as shown in Figure D-5.

The array support systems were constructed of polyvinyl chloride (PVC) because of its ability to act as an insulator while remaining relatively inert to petroleum products. Each thermistor array was constructed of 2-in. schedule 80 PVC for the vertical main frame and 3/4-in. schedule 40 PVC for the extending mechanical arm. To facilitate placement of the laser interferometer height measurement system into the tank, the vertical main frame was necked down to 3/4-in. schedule 80 PVC.

Extension and retraction of the mechanical arm were accomplished through the use of two control cables. Once positioned, the arm was secured to prevent movement during testing and product circulation. To accommodate uneven tanks, due to sagging or settling, one array was equipped with a level adjustment screw. This allowed for planar placement of thermistors between arrays.

Both arrays were equipped with at least 16 Omega OL-701 general purpose linear temperature probes (with resolution to 0.01°F), containing YSI 44018 thermistor composite.

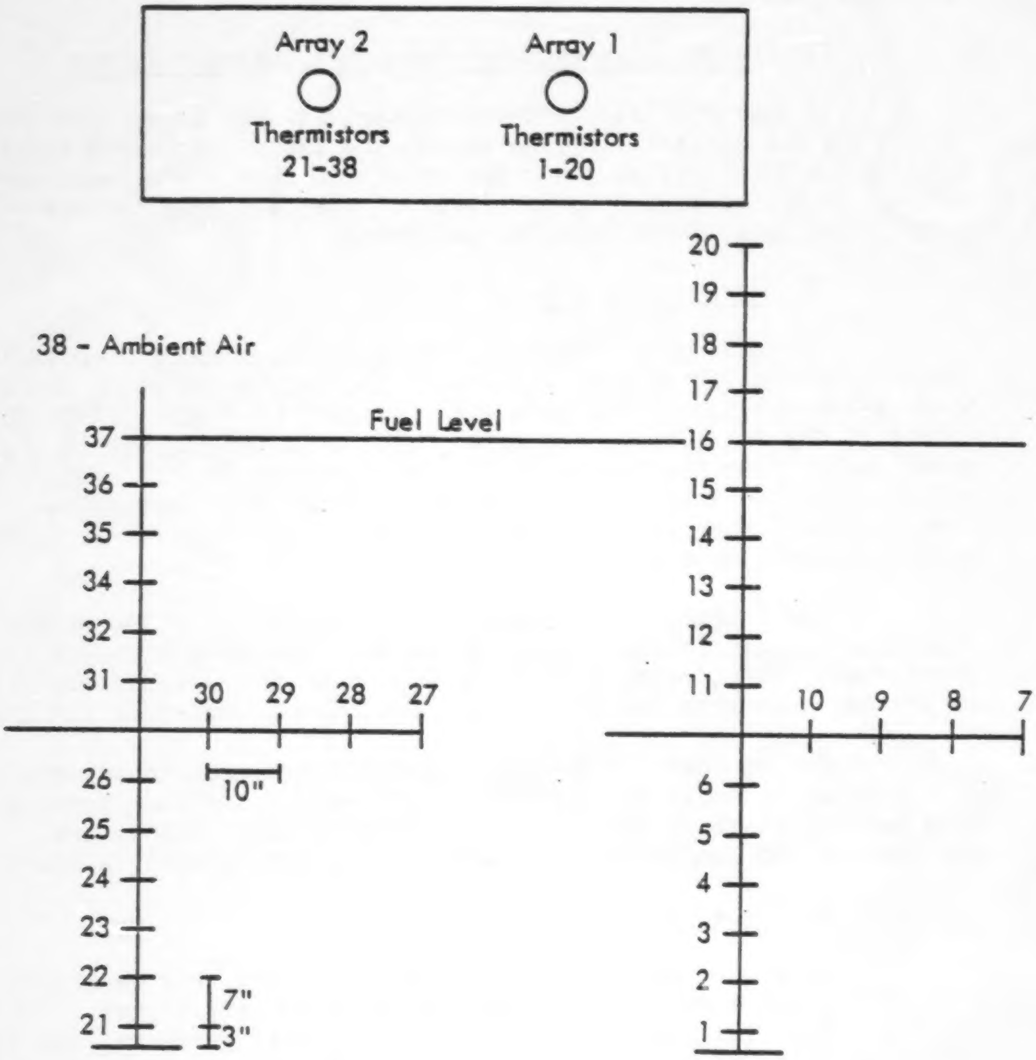


Figure D-5. Placement of thermistors on arrays by thermistor number.

Prior to installing the thermistors in the arrays, a calibration was performed on the sensors and the correction factor obtained for each was used in the final data analysis. A dewar temperature bath with a styrofoam insulation lid that secured two ASTM (0° to 30°C) mercury thermometers readable to 0.1°C was utilized. After the bath equilibrated, values of all thermistors and both thermometers were recorded. From the two ASTM thermometers, a bath temperature was established and correction coefficients were calculated for each thermistor.

2. Laser Interferometer Height Measurement System

A two-tube laser interferometer was used to monitor the product level from the center fill pipe during the tests. A quartz thermistor was attached to the tubes at the midpoint of the tank. A second quartz thermistor was installed at the center level of the tank from the end fill pipe as part of the laser interferometer equipment.

3. Circulation Pump

To facilitate Phase II testing during product circulation, a Heath Petro-Tite circulation pump was used. The suction inlet is placed at least 6 in. below the top of the tank while product is discharged (~ 25 psi) at the bottom of the tank, above any water. The discharge outlet is angled ~ 45 degrees upward from the bottom of the tank, attempting to create a spiral-like motion along the long axis of the tank. Petro-Tite recommended circulation time is 5 to 8 min/1,000 gal; during Phase II product was circulated for 16 h with continuous data collection.

The Petro-Tite method uses one thermistor in the bottom of the suction tube to monitor the tank temperature. Temperature changes from this thermistor, sensitive to 0.003°F, are used to calculate volume changes (due to thermal expansion and/or contraction) and to compensate for these changes.

During Phase II testing, attempts were made to operate the circulation pump while Array No. 1 (probes 1-20) was in the same opening. However, this was not possible due to physical constraints. Subsequently, one array was removed and temperature was monitored by the Petro-Tite thermistor.

4. Data Logging

Automatic and efficient recording of the data generated was accomplished through a portable microprocessor-based data logger. The Doric Digitrend 235, capable of handling up to 100 analog inputs, was equipped with remote mounting of two front-end modules RTD (FEM) to allow for maximum flexibility in instrumentation setup.

a. Linear Temperature Network

The thermistors used in this study undergo a large change in electrical resistance from small changes in temperature. This probe resistance is converted to a voltage through the use of a linear temperature network. A linear temperature network was utilized because it required a less complex output circuitry to convert sensor resistance to a useful temperature indicator while retaining a high degree of sensitivity. The original linear temperature network was redesigned by MRI to reduce the maximum linearity error from 0.4°F to less than 0.1°F over a range of 40° to 120°F.

b. Front-end Module Interface

The signal input wires from the linear temperature network were terminated into screw-down clamps in the remote front-end module (FEM) interface. Each interface can handle inputs from up to 20 sensors and is specified for an operating temperature range of 32° to 158°F. The remote FEM interface was then connected by a single cable to the FEM mounted inside the data logger, where the analog to digital conversion occurs.

c. Data Logger

The data logger used for this study was equipped with an optional math functions card which enabled on-site mathematical handling of the data. All data channels underwent a continuous 7-s synchronous scan, and a point average function was utilized to generate 1-min averages for each channel. All programs were protected against accidental changes by locking the data logger in the on (protect) position.

During testing, the data logger was operated by 110 VAC with all memory circuits backed up with battery power. An on-site hard copy of all data was obtained by using the thermal alphanumeric dot matrix printer on the data logger.

d. Microcomputer

A computer-readable record of the data was necessary due to the volume of data generated (approximately 2,500 by 40 data points). Due to the lack of a portable IBM PC-compatible microcomputer, an indirect route to the final PC-DOS data files was necessary. The serial output channel of the Doric logger was connected to an Epson HX-20 portable computer. A short BASIC program in the Epson waited for each 40-channel scan from the Doric and stored output on the built-in microcassette tape. Each tape side held about 90 min of data when using 1-min averages. The Epson also produced a printed log of each tape file ID as the data were recorded. Each file entry included the current date and time transmitted by the Doric as well as the time-averaged temperature for each channel.

5. Data Transfer

After returning to MRI, the tape data were transferred to disk files. A separate BASIC program read the data tapes and transmitted the data in ASCII over a local phone modem link to a Radio Shack Model I which used the Vidtex communication program to record the data on diskettes. A separate file conversion utility (Michtron TRSDOS/IBM Transfer) produced a PC-DOS 1.0 disk replica of the original Doric logger output.

The final conversion step was a BASIC program which spliced together the random length data files and rearranged the data into 1-h blocks in sequential data file format. Each data scan consisted of an alphanumeric date-time entry followed by 40 numeric temperature readings. Each hourly file name was defined as "LSTDdhh" where d is the final digit of the Julian day and hh is the hour (0 to 24 h time). This form allows the subsequent data handling programs to find any desired date block without operator assistance.

The contents of the final data files were transferred to a printer, and a manual check of randomly selected data periods verified that the various data transfers were free from errors. Scattered gaps occurred in the data when the data tapes were changed or as a result of unrecoverable cassette data blocks. Data recovery was > 95% for the overall test period.

Data were transferred to the HP110 3-1/2-in. discs and processed. The HP-110 is equipped with Lotus 1,2,3 and BASIC programming software. For field testing applications, the computer, disk drive, and printer are battery-powered.

C. Test Scenario

Field testing began late afternoon with the tank (8 ft x 27 ft) filled to approximately 40% nominal capacity (4,000 gal). The fuel was allowed to remain undisturbed for a period exceeding 48 h prior to testing. When testing commenced, each thermistor data point was evaluated every 7 s and the 1-min averages of these instantaneous values were recorded.

1. Preliminary Phase I

Initially, a single thermistor array was placed into the partially filled tank and allowed to collect data for a period exceeding 2 h. Nineteen thermistors were used for this period, five submerged and the remaining in the vapor space above the product. After the above data were collected, the tank was then filled to > 99% nominal capacity with continuous thermistor monitoring.

2. Phase I

The second phase of the testing involved implementing both thermistor arrays (33 thermistors submerged, three thermistors in the fill pipe vapor space), the laser interferometer height measurement system and the two quartz thermometer probes. Data from all acquisition systems were collected for a period of 19 h, without product circulation.

3. Phase II

At this point one thermistor array was removed and a Heath-Petro Tite circulation pump was installed and allowed to circulate for 16 h, during which data were collected from the available systems.

Ambient weather conditions and temperatures were monitored throughout testing on site and additional information was obtained through the local National Weather Service. Total testing and data collection spanned approximately 37 continuous hours.

D. Data Analysis Techniques

Temperature data received by the data logger were corrected using the calibration factors for each thermistor. The data were then plotted as a function of time.

E. Results

Four sets of test results are shown.

1. A plot of the ambient temperature data from thermistor No. 38 is shown in Figure D-6.

2. Plots of the volume changes observed from level measurements are plotted with the calculated temperature induced volume changes from the two thermistors associated with the laser system are shown in Figure D-7. The data are provided in Table D-5.

3. Plots of the temperature behavior of four thermistors located on array No. 2 are shown in Figure D-8.

4. A plot of thermistors 12 and 32 is shown in Figure D-9.

Two problems encountered in this testing limit the interpretation of the results. First, due to the temperatures of the fuel, ambient air ground, little or no temperature gradient was observed during the course of the testing. Second, the apparent electronics drift in the results of array No. 2 limit the comparison of the data collected at the end of the tank with the collected in the center. Nevertheless, some useful information can be extracted.

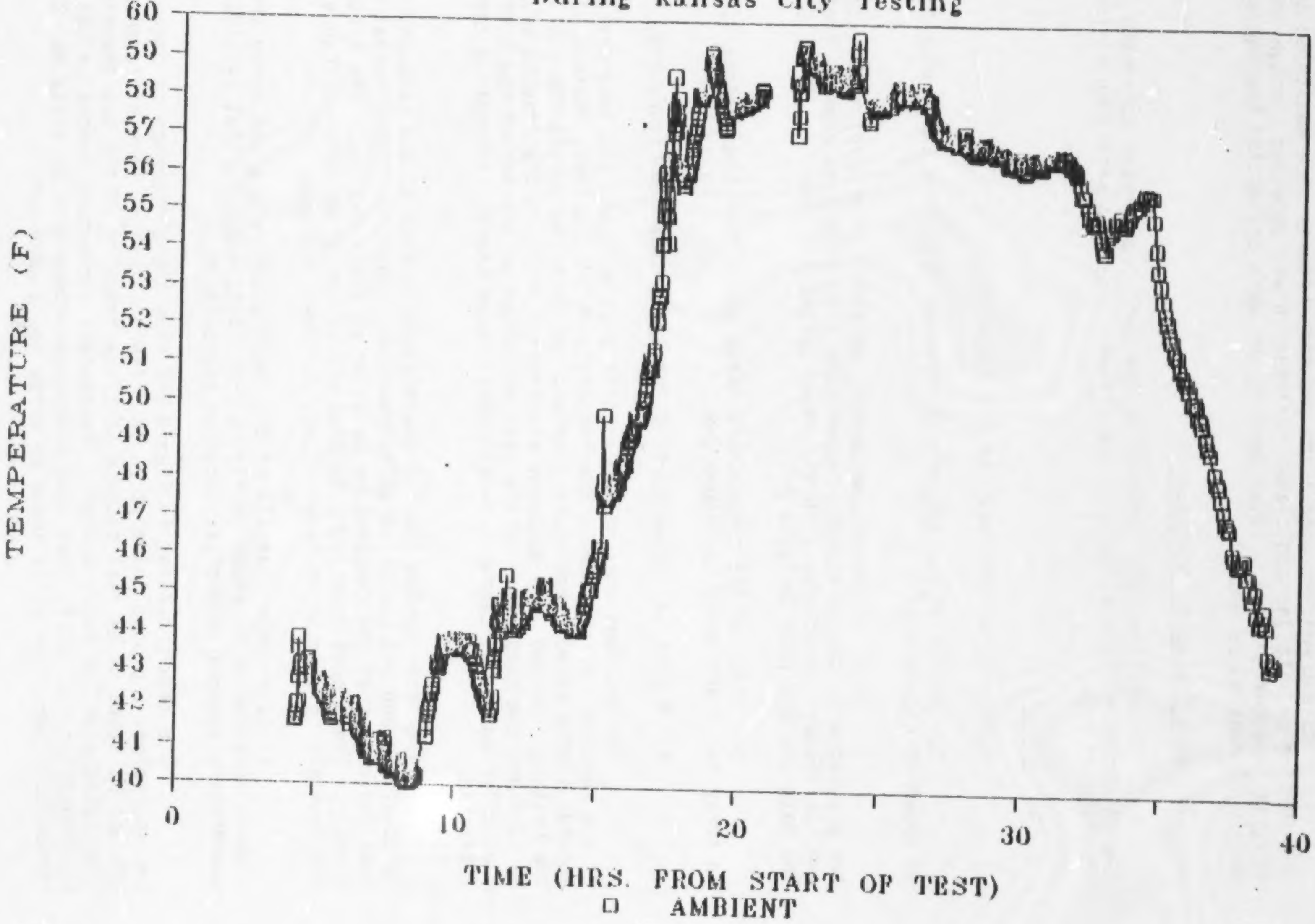
The laser system had two thermistors located at the vertical midpoint of the end and center which independently measured temperatures. These data indicate that the temperature behavior at these two locations tracks closely. These data also indicate that all of the product level changes are attributable to changes in temperature, as shown in Figure D-7.

It is evident that all of the thermistors on a given array track closely together as is shown in Figure D-8. This suggests that vertical temperature changes at a given location are uniform.

The data presented in Figure D-9 show the difference in behavior of two equivalently placed thermistors on different arrays. The differences shown are not believed to be real because of close tracking of the two thermistors associated with the laser system. Independent laboratory checks on the instrumentation did verify that some electronic components on array No. 2 were temperature sensitive while those on array No. 1 were not.

AMBIENT TEMPERATURE

During Kansas City Testing



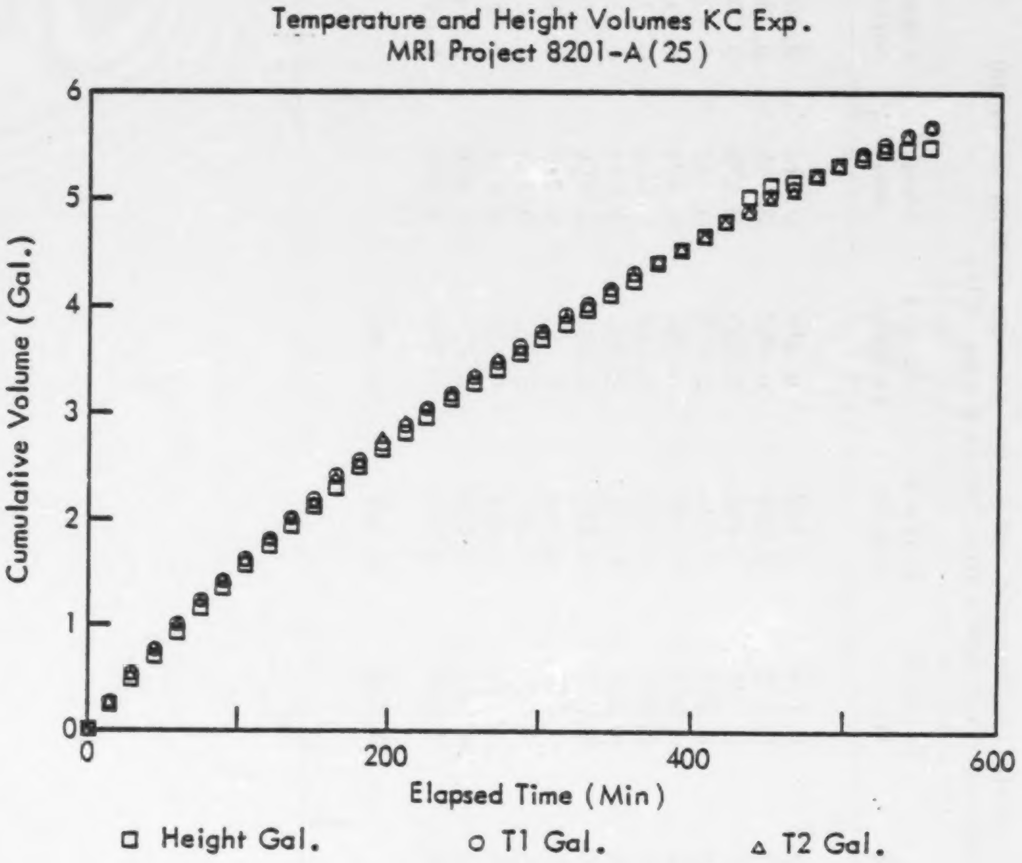


Figure D-7. Volume changes observed from level measurements.

Table D-5. Vertical Profile Temperature and Volume Changes During Stirring in a 10,000-gal Tank Containing Unleaded Gasoline

Time	Delta T top	Delta T middle	Delta T bottom	Delta V top	Delta V middle	Delta V bottom	Cumm V top	Cumm V middle	Cumm V bottom
1700	0.188	0.179	0.188	0.114	0.108	0.114	0.114	0.108	0.114
1715	0.169	0.163	0.160	0.102	0.099	0.097	0.216	0.207	0.211
1730	0.179	0.166	0.163	0.108	0.101	0.099	0.325	0.308	0.310
1745	0.144	0.160	0.172	0.087	0.079	0.104	0.412	0.405	0.414
1800	0.135	0.141	0.132	0.082	0.085	0.080	0.494	0.490	0.494
1815	0.119	0.132	0.132	0.072	0.080	0.080	0.566	0.570	0.574
1830	0.129	0.166	0.116	0.078	0.101	0.070	0.644	0.671	0.644
1845	0.110	0.091	0.150	0.067	0.055	0.091	0.711	0.726	0.735
1900	0.129	0.147	0.085	0.078	0.089	0.051	0.798	0.815	0.786
1915	0.081	0.078	0.135	0.049	0.047	0.082	0.838	0.662	0.868
1930	0.100	0.129	0.085	0.061	0.078	0.051	0.898	0.940	0.920
1945	0.103	0.063	0.119	0.062	0.038	0.72	0.961	0.978	0.992
2000	0.094	0.116	0.078	0.057	0.070	0.047	1.018	1.049	1.039
Mean				0.078	0.081	0.080			

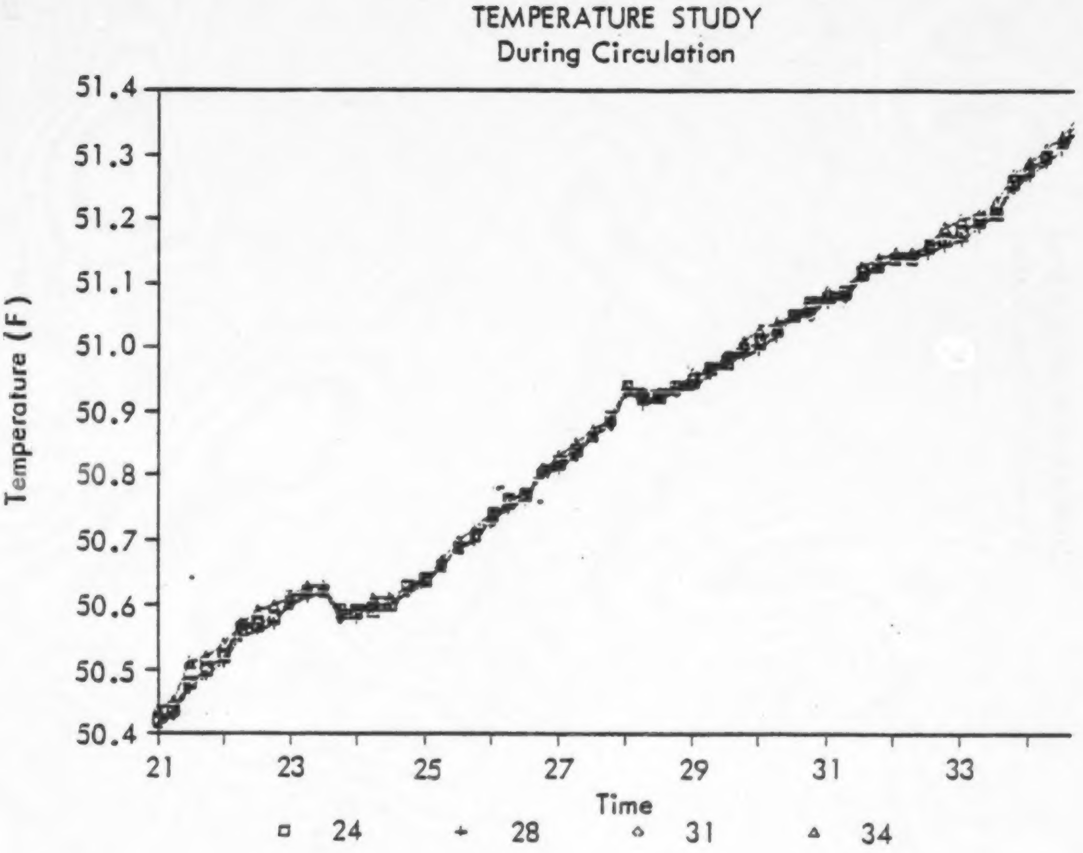


Figure D-8. Temperature behavior of four thermistors.

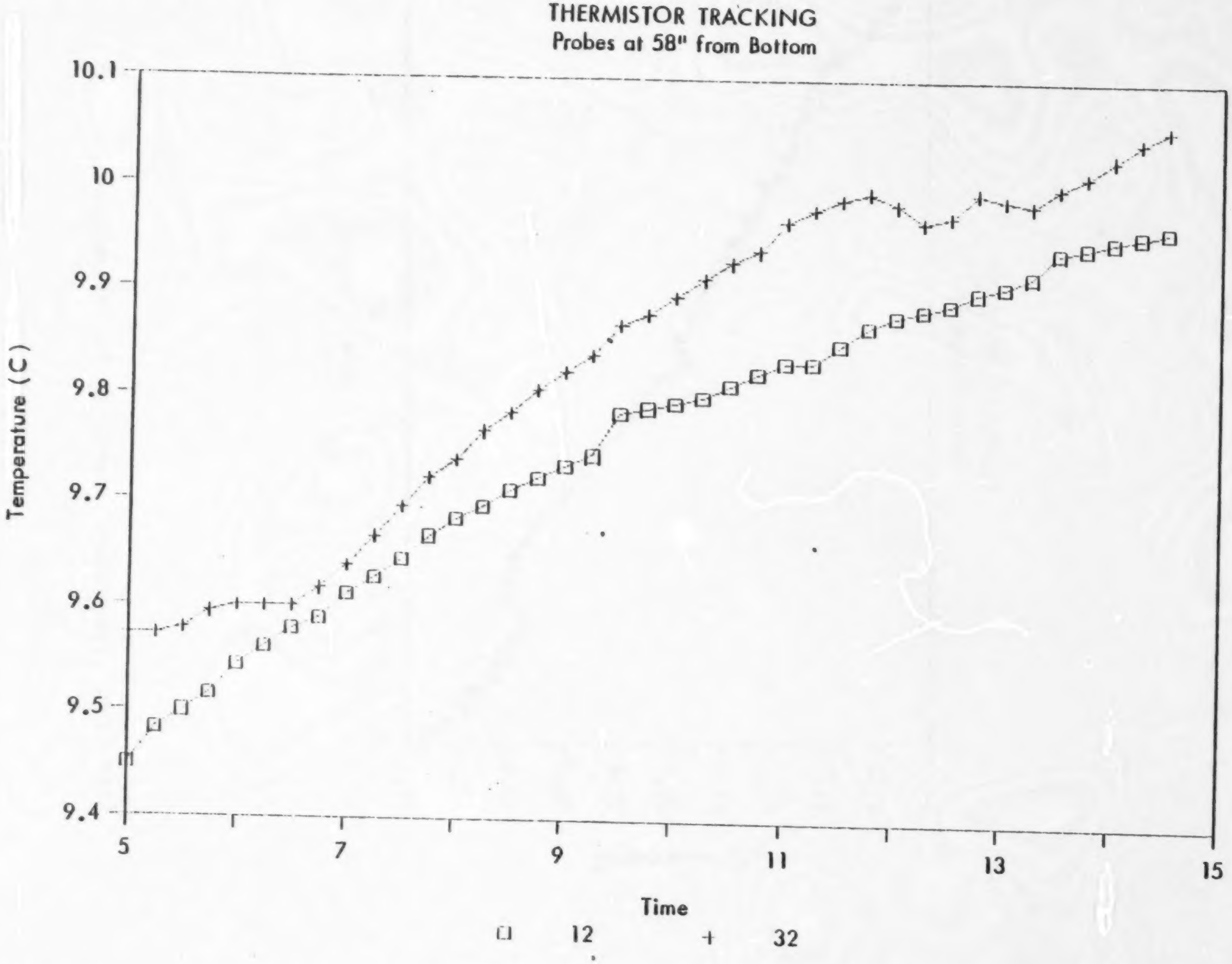


Figure D-9. T[illegible]istors 12 and 32.

Although the data were seriously compromised, they do suggest that under the conditions of the test, a single thermistor located at the midpoint would have predicted volume changes quite well. Since little gradient existed in the tank, the results of stirring were uninformative.

IV. MIXING COMPLETENESS STUDY

This study presented additional data supporting the conclusion that the circulation procedures used by the Petro-Tite system produce uniform temperature behavior, both vertically and horizontally.

A. Experimental Approach

Two sets of data were collected. The first involved the use of a modified Petro-Tite system. Three thermistors were mounted vertically in the access hole of the tank. Temperatures were monitored at 15-min intervals during the test.

The second set of data was collected using three thermistors placed along the top of the tank. In this case, three Petro-Tite units were in the tanks, but only one end and the center unit were used to circulate product. Data were collected at 15-min intervals.

B. Instrumentation

Petro-Tite equipment was used to collect both data sets. Temperatures were recorded manually from the standard Petro-Tite temperature units.

C. Data Analysis

The temperature changes were first converted to the equivalent volume changes for the tank being tested. The data were plotted as cumulative volume change versus time and volume change versus time for each thermistor. The plots were then examined visually to determine trends. The volume changes for each thermistor were calculated for the entire tank and for the segment represented by each thermistor.

D. Results

The results of the measurements from the vertical array are given in Table D-5. Plots of the cumulative volume change are shown in Figure D-10. A plot of the volume changes for each thermistor for each 15-min interval is shown in Figure D-11.

Analysis of variance of the temperature changes in the vertical profile showed no significant differences among the thermistor at different depths. The F statistic was 0.11 with 2 and 24 degrees of freedom. The estimated standard deviation of a 15-min temperature-related volume was 0.0133 gal. The mean temperature-related volume change per 15-min period for each thermistor is shown at the bottom of Table D-5.

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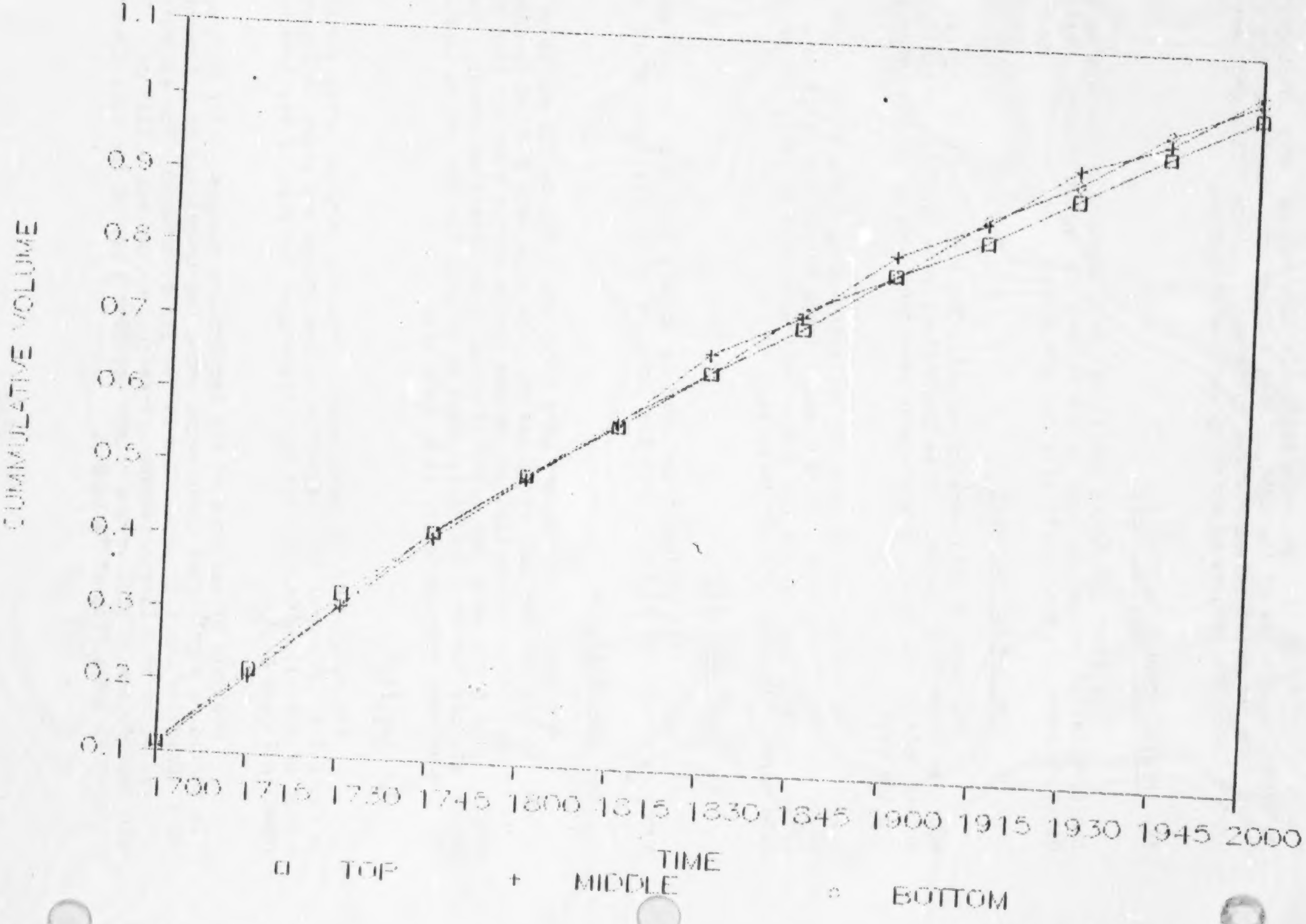

Figure D-10. Cumulative volume change

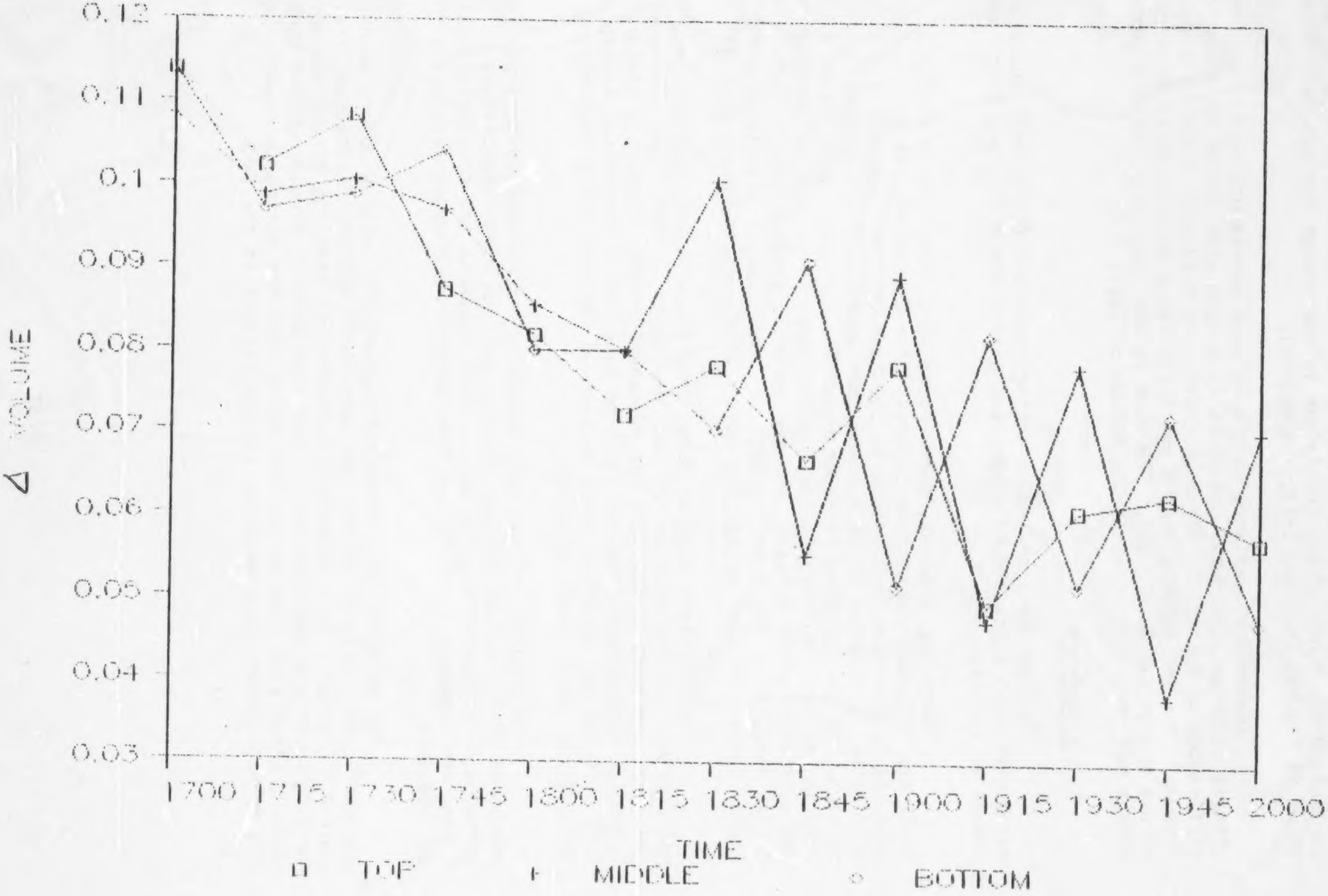

Figure D-11. Point-to-point volume change, vertical array.

The results of the measurements from the horizontal array are given in Table D-6. Plots of the cumulative volume change and volume changes are shown in Figures D-12 and D-13, respectively.

Analysis of variance on the volumes corresponding to temperature changes at three horizontal positions in a tank also showed no significant differences by position. The F statistic was 0.72 with 2 and 18 degrees of freedom. The estimated standard deviation for a 15-min temperature-related volume change was 0.0088 gal. The mean volume resulting from the temperature change per period is shown at the bottom of Table D-6.

E. Discussion

The test data collected during these two field tests support the assumption that circulation is complete within the mixing and high level phases of the test.

There are, however, some limitations presented by the data. First, since the absolute temperature accuracy of a Petro-Tite thermistor is ± 3.0°F, absolute temperature differences in the tank were not determined. A complete multipoint calibration of each thermistor used would be required for this comparison. Second, nothing is known about the horizontal profile of the tank used in the vertical profile test or the vertical profile of the tank used in the horizontal profile test. For the vertical profile test, the tank had been filled immediately prior to the test. The horizontal profile tank had been tested three days earlier and had been sitting undisturbed since that time.

These factors suggest that large temperature gradients were probab not present, and the conclusions must be judged in that light. However, since the pumps add heat to the tank (as evidenced by the increasing temperatures), irregular temperature patterns would be expected if mixing was incomplete. That this was not observed lends support to the conclusion that mixing during the testing was at least adequate.

The analysis of variance showed no significant differences in temperature-related volume changes for the vertical array thermistors. The observed differences were quite small, which supports the conclusion that the mixing was adequate to attain uniform temperature changes vertically throughout the tank.

The observed differences in temperature-related volume changes for the horizontal array of thermistors were small and not statistically significantly different. This supports the conclusion that the mixing was adequate to attain uniform temperature behavior horizontally throughout the tank. Together, these data lead to the conclusion that the mixing succeeds in attaining uniform temperature behavior for the product in the tank.

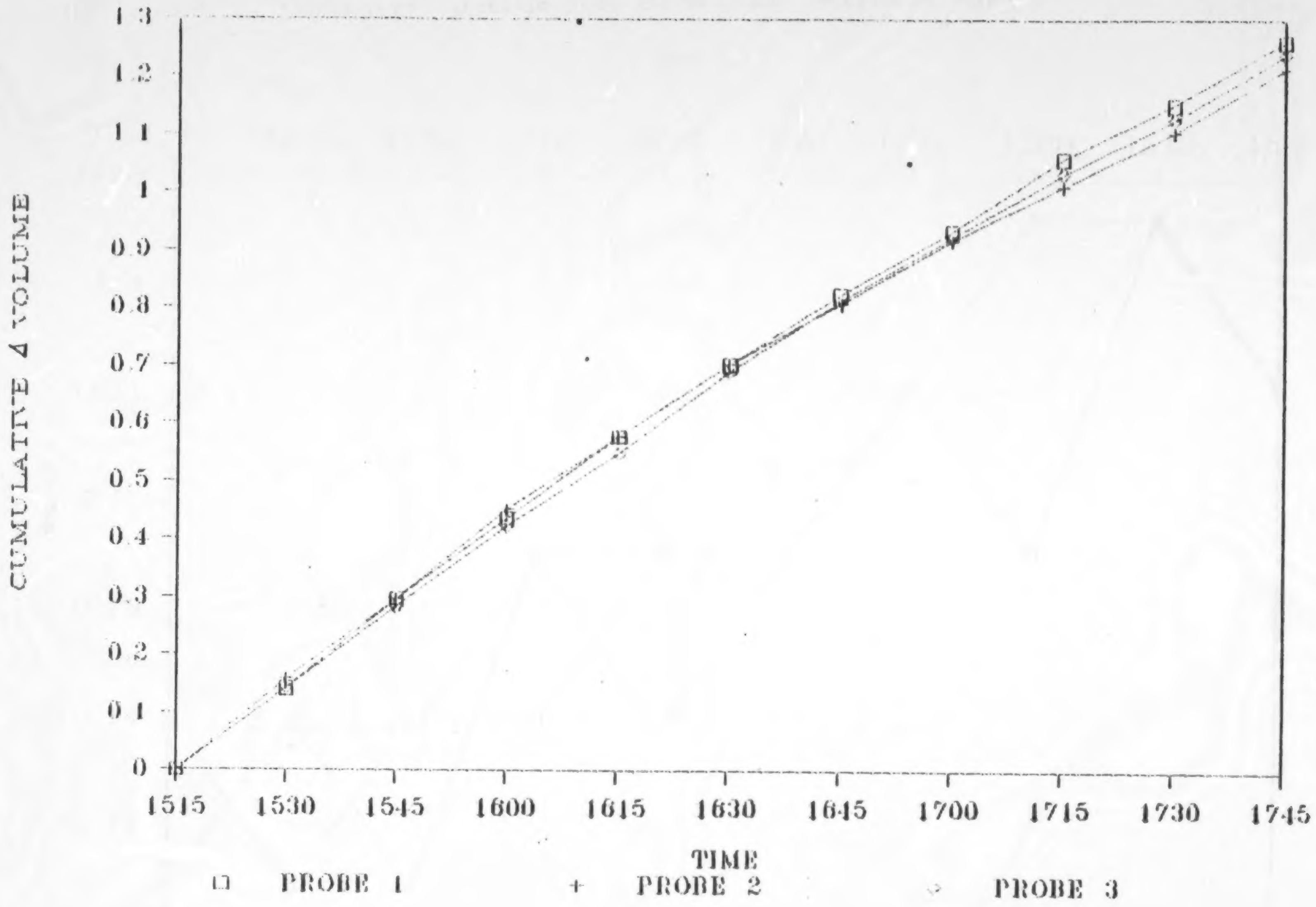

Figure D-12. Cumulative volume change, horizontal array.

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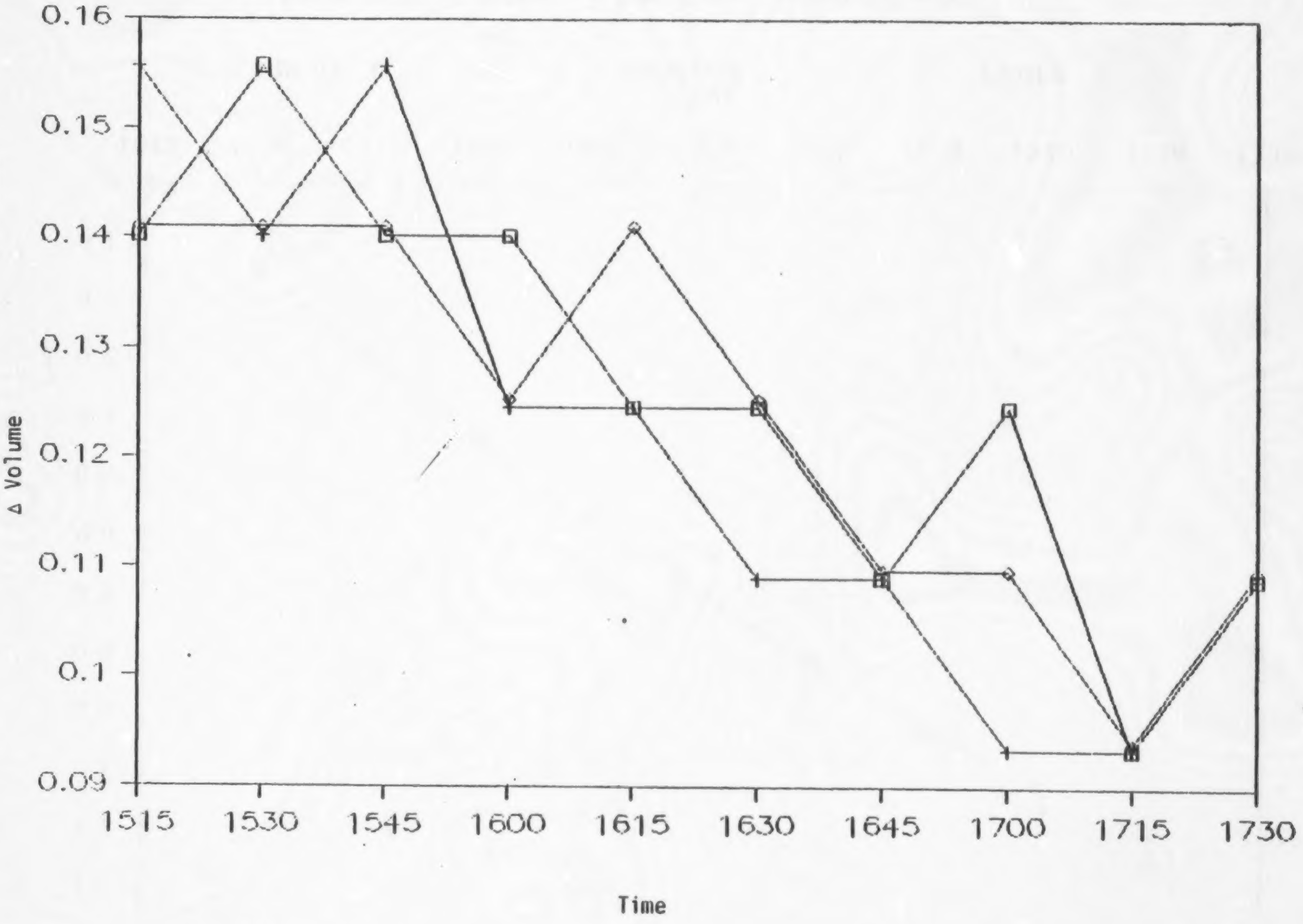

Figure D-13. Point-to-point volume change, horizontal array.

Table D-6. Horizontal Profile Temperature Changes During Stirring in a 10,000-Gal Tank Containing Aviation Fuel (Two Circulation Pumps Were Used)

	Convert to Temperature								
Time	Δ Digit probe 1	Δ Digit probe 2	Δ Digit probe 3	Δ Volume probe 1	Δ Volume probe 2	Δ Volume probe 3	Cum vol. probe 1	Cum vol. probe 2	Cum vol. probe 3
1515							0	0	0
1530	9	10	9	0.140	0.156	0.141	0.140	0.156	0.141
1545	10	9	9	0.156	0.140	0.141	0.29	0.29	0.28
1600	9	10	9	0.140	0.156	0.141	0.43	0.45	0.42
1615	9	8	8	0.140	0.125	0.125	0.57	0.57	0.54
1630	9	8	9	0.125	0.125	0.141	0.70	0.70	0.68
1645	8	7	8	0.125	0.109	0.125	0.82	0.81	0.81
1700	7	7	7	0.109	0.109	0.110	0.93	0.91	0.92
1715	8	6	7	0.125	0.093	0.110	1.05	1.01	1.03
1730	6	6	6	0.093	0.093	0.094	1.15	1.10	1.12
1745	7	7	7	0.109	0.109	0.110	1.26	1.21	1.23
Mean				0.140	0.135	0.138			

Probe No. 1 - no pump--tank end
Probe No. 2 - center circulation pump
Probe No. 3 - opposite end from No. 1, circulation pump

The vertical profile test results shown in Figure D-12 show somewhat more erratic results than were expected for a small (1000-gal) tank. Calculation of the volume correction using the top thermistor only versus a average of all three thermistors gives values of 0.605 and 0.624, respectively, for the 2-h test. This difference of 0.019 gal seems well within the range of variability experienced in the development study and expected for the national survey test results.

The horizontal profile results are very consistent. The cumulative volume changes using probe No. 3 (the master probe in this test) versus the average gave essentially identical results for the 2-h test. In this case two circulation pumps were used which may have improved the circulation pattern . A 10,000-gal tank does not normally require two circulation pumps.

There are some limitations to the data in that not all relevant initial conditions could be tested. However, the data obtained support the conclusion that the mixing achieves uniform temperature behavior in the tank.

APPENDIX E

SITE VISITS TO OBSERVE TESTS

A. Objectives

Arrangements were made to visit each of the sites tentatively selected for the pilot study. The primary purpose was to assess the method in terms of its suitability for use on the National Survey. Methods judged to present satisfactory potential for the National Survey were selected for further testing. A summary of each site visit follows.

B. Leak Lokator Site Visit

A site visit was conducted on April 18, 1984, to observe the Leak Lokator system in operation at a site near Philadelphia, PA. The system was operated by Hunter Environmental. Dan Heggem and Mike Kalinoski from EPA and Ken Wilcox from MRI observed the test. The principal contacts from Hunter Environmental were Donna Hymes and Joyce Rizzo.

1. Description of Method

This method is based on measurement of the level of liquid in the tank. The sensor is a patented buoyancy probe connected to a balance that is suspended over the tank fill pipe. As the liquid level changes occur, the buoyancy of the sensor changes and the change is measured by the balance. The changes are monitored electronically and transmitted to a signal processor where they are continuously recorded on a strip chart. The temperature of the tank is continuously monitored with a single thermistor which is located at the midlevel of the tank. The temperature is also recorded on a strip chart. More sensitive temperature readings from a digital voltmeter are manually recorded on the chart at periodic intervals. The system is calibrated prior to each use and again at the conclusion of the test by inserting a metal rod of known volume into the tank. This allows the effect of the known volume change to be calculated and removes the necessity to know exact tank dimensions.

The precision of the method is stated to be 0.05 gal/h if testing is conducted on an overfilled tank. The test can be conducted on a partially filled tank, but the precision of the method will be lower, particularly with large tanks. The normal procedure when testing a tank is to test with product level raised to around 28 in. in the fill pipe. This checks the overall system tightness including the piping system which leads to the dispenser. If a leak is observed, then a second test is conducted at a level just above the top of the tank to test only the tank. This information is used to differentiate between leaks in the tank and leaks in the piping system. The piping system can also be separately pressurized if necessary.

2. Observations

This method is well developed and the operator, Hunter Environmental, has considerable experience in conducting tank tests. Over 12,000 tanks have been tested over the past 3 yr. Hunter currently has 15 units operating in the field and plans to add several more. Hunter can generally be at a site within one week's notice and can test several tanks at one location in one day. The only adverse weather condition which seems to present a problem is high wind. This condition causes small movements in the balance which are recorded as noise on the strip chart recording the level changes.

Hunter also places a high value on the training of its personnel. This training includes a thorough knowledge of tank plumbing systems as Hunter considers (correctly) an understanding of plumbing essential for correct interpretation of results.

3. Recommendations

MRI recommends the Leak Lokator method for further study. The system is well designed, it seems to have the requisite accuracy, and Hunter has had considerable experience in conducting testing. In addition, since Hunter has 15 units available, it provides the necessary flexibility in meeting test demands.

Since Hunter does not sell or lease its equipment, any testing using this method will have to be contracted through them. Some additional data relative to the sensitivity and accuracy of the method have been requested from Hunter.

C. Certi-Tec Site Visit

A site visit was conducted on April 20, 1984, at the Fuel Recovery Company, Inc., St. Paul, MN, to observe the Certi-Tec tank testing system in operation. Fuel Recovery's main business is the recovery of spilled petroleum products and the restoration of ground water supplies which have been contaminated. The test was observed by Mr. Tom Muir from EPA and Dr. Ken Wilcox from MRI. The principal contact from Fuel Recovery was Mr. Dan Bigalkie.

1. Description of the Method

The Certi-Tek method is based on measurement of the level of liquid in the tank by measuring pressure changes which occur within the tank as a result of loss of product. A pressure transducer is attached to a rod which is lowered into the tank until it rests on the bottom. The rod is then clamped to the top of the tank. Five thermistors are also attached to the rod at intervals of approximately one-fifth of the diameter of the tank. Temperature and pressure readings are then collected by a data logger which updates a CRT every 5 s. The test values are printed every 15 min on a tape. Although the data logger did not average the readings during the site visit, it does have this capability. After data are collected for 1 to 2 h, the data from the tape are entered into a computer manually and the loss of product is calculated.

The 6-ft diameter steel tank observed during this test was not buried. The capacity of the tank, which was filled with water, was 1,000 gal. The test was conducted in the shop area of Fuel Recovery Company. The testing was conducted by introducing a "leak" by opening a valve which was located at the bottom of the tank and capturing the water with a bucket for volume measurement at the end of the test. After approximately 1 h of recording data, a measured volume of 0.50 gal had leaked from the tank. The computed leak value was 0.59 gal.

2. Observations

This test method seems to have high potential for use in leak detection of underground storage tanks. One of the major attractions of the method is the relatively low cost of the equipment. The method is a simple one and the equipment can be installed at the test site very quickly. The system as it is now configured at Fuel Recovery needs some further refinement and the company states that they are continuing to work on this. There is no field test data available so that evaluation of potential problem areas cannot be concluded at this time. Refinements which could be made include the addition of a continuously recording strip chart and the direct input of data to the computer. Considerably more precision and accuracy data will need to be collected before the method can be used for routine tank testing.

3. Recommendations

MRI recommends the Leak Lokator method for further study. Fuel Recovery is in a position to provide this support and will have worked out some of the details regarding its use before the pilot study begins.

If the method is selected for the National Survey, EPA should consider options such as purchase or lease of this equipment for the study.

D. Varian Helium Detector Site Visit

A site visit was conducted on May 15, 1984, at Smith and Dennison, Haywood, CA, to observe a tank test using the Varian Spy 2000 leak detection system. The test was observed by Ken Wilcox, MRI, and Tom Muir, EPA. Bill Burkhardt of Smith and Dennison and Jack Farmer of Varian also observed the test.

1. Description of the Method

Helium, which diffuses readily through soil and even concrete or asphalt, is used to pressurize the tank to be tested. The helium, which will diffuse rapidly through the leak and rise to the surface within a matter of minutes, is detected by an instrument based on mass spectrometric techniques. In most cases it is necessary to drill small holes in the concrete or asphalt covering the tank. A matrix of holes is drilled for the initial evaluation. Additional holes are then drilled in areas where helium is initially detected. With experience, the operator can learn to make judgments as to the size of the leak, as well as its approximate location.

The method seems straightforward. and trained technicians should be able to operate the monitors without difficulty. The tank must be drained completely in order to test the bottom, which may represent some risk in areas where high water tables exist. Quantitative estimates of the leak rate can be obtained using a differential pressure system developed by Smith and Dennison.

2. Observations

The tank tested was constructed of fiberglass and was believed to be leaking because water had been found in the tank to the extent that it was necessary to pump out an estimated 400 gal/wk. Approximately a year earlier the tank had been uncovered and the fittings on the top checked for evidence of leaks. The tank had been installed approximately 10 yr earlier. The water table in the area was observed to be above the tank while it was uncovered the previous year, but based on evidence in a sump hole near the tank, the water table was estimated to be approximately 4 ft above the bottom of the tank during the present test.

Initially, a grid was laid out above the tank at 5-ft intervals. Helium was used to pressurize the tank to approximately 5 psig through the dispenser which had been disconnected. The vent pipe for the tank was also capped off.

Holes were drilled in the concrete pad above the tank on the grid marks using a 5/8-in. concrete bit. Two helium detectors were used to monitor the leaks. The Varian Model Spy 2000 owned by Varian was operated by Jack Farmer of Varian, and a similar instrument owned by Smith and Dennison was operated by Bill Burkhardt.

During the test, each hole was monitored with a leak detector and the maximum concentration obtained at each hole was recorded on the grid. If the detector went off scale, a shorter sample time was used. All of the holes were then monitored for the shorter sample time. Additional holes were drilled where high concentrations of helium were detected and the test sequence was repeated. The resulting pattern was then used to determine the approximate leak location and obtain an estimate of its magnitude. Some operator judgment is necessary in selecting additional holes and in assessing the data.

3. Recommendations

This test method is extremely sensitive for pass/fail determinations. Since helium diffuses readily through very small holes, "leaking" pipe joints caused by failure to dope the threads during assembly could lead to a false positive result even though the leaking of product through such a joint would be negligible. Additional data can be collected if the tank fill pipe, dispenser connections, and vent pipe can be adequately sealed. Further work is proceeding on this technique. In spite of the extreme sensitivity of the technique, the helium leak system should be evaluated in the pilot study. It is readily portable and can be easily operated by a trained technician. The cost for the instrument is relatively high, but it may be possible to make lease arrangements for the equipment.

E. Site Visit, National Institute for Petroleum and Energy Research (NIPER)

A site visit was conducted on May 2, 1984, to the National Institute for Petroleum and Energy Research (NIPER) in Bartlesville, OK. Soil coring and drilling procedures used by NIPER to locate naturally occurring oil pools were observed. It was hoped that these techniques could be adapted to identifying leaking fuel tanks. NIPER has had considerable experience in this ar and feels that the technique shows strong promise. The site visit was conducted by Mike Kalinoski, EPA and Ken Wilcox, MRI. The principal contacts at NIPER were Herbert Carroll, Jr. and Gene Collins.

1. Description of the Method

The presence of specific trace organic compounds can be detected in both soil core samples and ground water samples taken in the vicinity of storage tanks. Portable gas chromatographs using a variety of detectors can be used on site to detect low ppb levels of contaminants. In both cases small holes or wells are drilled around the perimeter of the storage area. Soil cores obtained are transferred to airtight storage containers. After a suitable equilibration time, a sample of the headspace in the container is analyzed by the gas chromatograph. A sample line may also be lowered into the hole to detect the presence of hydrocarbons in the ground if desired. Ground water samples obtained from these wells may be similarly analyzed for specific species which are volatile and of low solubility in water. If a series of holes is drilled systematically, it is possible to identify the probable source of the leak. If a more precise determination is required, the samples can be returned to the laboratory and a full extraction with GC/MS analysis performed.

The ability of this method to detect hydrocarbons is high. However, the specific source of the hydrocarbons could be subject to questions. Portable instrumentation is readily available and has a high sensitivity if properly used. However, where the storage tanks are located beneath concrete drives, as may be the case for most service stations, the drilling of enough holes to locate the leak may be impractical. Useful information regarding the soil characteristics around the tank could also be obtained from the coring operation.

2. Observations

During the visit to NIPER, a test drilling was observed to a depth of several feet. The drill can be mounted on a trailer and pulled to the test location. A fully equipped van with a power supply and gas chromatograph is available to perform on-site analysis so that decisions as to the location of the next test hole can be determined.

A GC analysis was also performed by NIPER in the laboratory to demonstrate that capability. The analysis time was around 10-12 min per sample. The results were recorded on a strip chart so that the sample signature could be visually compared with known standards.

3. Recommendations

Since the signatures of a leaking fuel tank have not been reliably determined, it seems unlikely that the method can be used without further development. Nevertheless, it is desirable that at least a few core samples be collected from sites where fuel is known to have been leaking and analyzed The number of samples to be collected may depend on the available funds.

Since the NIPER personnel seemed to have very positive feelings about this technique, they were asked to prepare a short proposal to provide details of what could be done and estimate costs. This proposal will be evaluated before final selection for the pilot study is completed.

F. Petro-Tite Site Visit

A site visit to O. H. Materials was conducted on May 9, 1984, to observe the Petro-Tite method in operation on a company owned tank. Dan Heggem, EPA, and Ken Wilcox, MRI, observed the test. Petro-Tite has some 600 franchised dealers in the United States. The method, known in the industry as the Kent-Moore test, has probably been used to test more tanks than any other tank testing method. The National Fire Prevention Association (NFPA) test code is based largely on this test method.

The principal contacts at O. H. Materials was John Copus. O. H. Materials was recommended by the Petro-Tite Company as being one of their better testing groups. Jack Stillwagen of the Heath-Petro-Tite Company also observed the test.

1. Description of the Method

The Petro-Tite test is a hydrostatic test that compensates for temperature, pressure, and viscosity variations. The Petro-Tite test consists of exerting a pressure head of 5 lb on the tank. A pump is used to circulate the product throughout the tank in order to promote a uniform temperature. Using a thermal sensor, the temperature changes are monitored to account for the expansion and contraction of the product. This test is conducted by measuring all product added or removed from the standpipe in order to maintain a constant head. By comparing the product added or removed with anticipated volumetric changes resulting from temperature variations, it is possible to detect leaks in the tank system.

For storage systems with submerged pumping, the Petro-Tite test must be run separately on the tank and on the piping to give good results. On suction delivery tank systems, the test checks the entire system simultaneously.

The Petro-Tite test requires several hours (usually one work day) to complete. Generally, during the first few hours of the test, there is a drop in the standpipe level because of the increase in the internal tank pressure. This is compensated for by reducing the tank pressure after 2 h to control tank expansion. A relatively difficult test, it must be performed by skilled technicians. Shutdown of the facility is required during the test.

2. Observations

The equipment and installation of the equipment on the tank were observed upon arrival at the test site. The process seems straightforward, except that for conditions of high water table the fuel head on the tank is quite high. During the test observation the water table was within an inch or two of the surface requiring the fuel reservoir to be located approximately 18 ft above the ground. A scaffolding had been erected for this purpose. This high head required that the vent pipe be capped to prevent overflow.

PB86-224078 EPA/560/5-86/014 DEVELOPMENT OF A TANK TEST METHOD FOR A NATIONAL SURVEY OF UNDERGROUND STORAGE TANKS (REVISED DRAFT). (FINAL REPT. JUN 85-JAN 86) / H. K. WILCOX, ET AL. MIDWEST RESEARCH INST., KANSAS CITY, MO. MAY 86 300P

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2. Observations

The equipment and installation of the equipment on the tank were observed upon arrival at the test site. The process seems straightforward, except that for conditions of high water table the fuel head on the tank is quite high. During the test observation the water table was within an inch or two of the surface requiring the fuel reservoir to be located approximately 18 ft above the ground. A scaffolding had been erected for this purpose. This high head required that the vent pipe be capped to prevent overflow.

After installation of the equipment the product was stirred for about 1 h to stabilize the temperature. The temperature was recorded manually from a digital thermometer. Attempts to record the volume changes associated with the initial 5-lb pressure required addition of considerable amounts of fuel to the reservoir. This rapid drop continued for several hours, but the rate was decreasing steadily, indicating that the tank end deflections were stabilizing. Unfortunately, it was not possible for the observers to remain at the site long enough for complete stabilization to occur with the reduction to 4 lb of pressure for the test.

Working on a high scaffolding such as this in a high wind, as was the case during this observation, could lead to difficulty in accurately reading the fuel level. Considerable shaking of the platform occurred.

3. Recommendations

Since the Petro-Tite method has been used widely and is recognized in the industry, it could be included in the pilot study program for comparison purposes. The test method can be applied to a "tank only" test only if the plumbing to the tank can be disconnected. Otherwise both the tank and plumbing are tested at the same time. Partially filled tanks cannot be tested.

G. ARCO Site Visit

A site visit was conducted at the Atlantic Richfield Research Center in Harvey, IL, for the purpose of observing the ARCO tank testing system in operation on one of their tanks. The test was observed by Mike Kalinoski f EPA, and Joel Pavelonis and Ken Wilcox from MRI. The principal contact at ARCO was Tom Collins.

1. Description of the Method

The ARCO method is based on detecting level changes in a partially filled tank. The sensor consists of a photocell contained in an "ink well" and a light source. These are attached to a hinged float in such a way as to change the depth of the ink over the photocell when changes in level occur. This changes the light attenuation which is detected with a voltmeter. The voltage changes are recorded on a strip chart as the test progresses. The system is calibrated by adding known volumes of fuel to the tank.

One of the novel features of the method is that the float level can be positioned in the tank at a point where it is insensitive to temperature changes. This is due to the fact that changes in level caused by expansion or contraction of the product with temperature are exactly compensated by changes in the density (and float buoyancy) with temperature. This eliminates the need for temperature measurements and corrections.

2. Observations

The test method appears to be extremely sensitive, making it possible to test a partially filled tank in a period of a few hours. The equipment can be installed fairly quickly. ARCO has tested approximately 6,000 tanks using the technique and has verified the test results in several cases by removing the tanks for inspection following the test. They are currently in the process of franchising independent groups to provide the testing at sites other than those controlled by ARCO.

3. Recommendations

The ARCO system should be studied further. It has considerable sensitivity, it is simple to operate, and the equipment costs do not seem to be excessive. Some precision and accuracy data are available from Arco.

H. Underground Radar Site Visit

On May 10, 1984, Ken Wilcox visited the University of Ohio, Columbus, to discuss the possible application of underground radar to locating leaking storage tanks. The principal contact there was Dr. Jon Young.

1. Description of the Method

The underground radar system sends radar waves into the ground which are then reflected back to the surface by various objects which may be buried there. The signals receive computer enhancement and are printed out showing differing densities and depths of buried objects. The waves can reach down to around 15 ft, but unfortunately resolution decreases as the depth increases. An experienced operator can learn to recognize specific types of objects and their composition from the reflected waves. The success of the method is largely a function of the skill of the operator. A hand-held unit which does not use computer enhancement is also available.

2. Observations

Underground radar has not been applied to the detection of liquid hydrocarbon leaks. It has been used to detect water and natural gas leaks. In both of these applications, leaks are detected by locating areas where soil characteristics are different from those in the surrounding areas. It is not clear that a pattern characteristic of a leaking storage tank can be easily identified. The cost to construct a radar unit and collect sufficient data to develop the method could cost as much as $100,000. A hand-held unit might prove useful, however, in locating piping system, etc., around service stations.

3. Recommendations

This method should be considered for inclusion in the pilot study. Although the state of the art of this method, its high cost, and long development time preclude its use at this time, the method shows some promise and has some attractive features if it can be made to work.

APPENDIX F

SOIL ANALYSIS

Soil samples were collected at Fort Lewis, Tacoma, Washington, during the pilot study. The coring was conducted by Norton Corrosion of Seatt Washington. The soil analysis was conducted by Warren Rogers Associates, Inc., Newport, Rhode Island, and the National Institute for Petroleum and Energy Research (NIPER), Bartlesville, Oklahoma. Four holes were drilled at two of the test sites, 8C25 and 4194. Two soil samples were taken from each core, one at midpoint (6 ft) and one at the bottom (12 ft). In addition to these samples, MRI took four surface samples at each site. Two of the surface samples were soil composites taken near the tanks at 1-ft and 2-ft depth. The other two were taken at 50-ft and 100-ft distances from the tanks. All soil samples were dry, sandy, and well drained.

The samples were analyzed for percentage moisture, conductivity, pH, sulfides, and number of hydrocarbons present (by Warren Rogers only). NIPER analyzed the surface samples taken at 50 ft and 100 ft from the tanks. The results of the analysis are shown in Table F-1.

Warren Rogers Associates determined the mean age and the probability of a leak from the analysis and other system factors. The mean ages to leak for site 8C25 ranged from 14.9 to 16.5 years, if the surface samples were excluded. For site 4194, they range from 15.7 to 17 years, also excluding the surface samples. In both cases, surface samples yielded slightly higher mean ages (17.7 and 17.8 years) due to slightly less acidic and less conductive soils in those samples.

The samples were dry. Hence, the mean ages were computed for saturated soils of like chemical composition. This allows for the possibility of fluctuating water tables. These ages range from 10.5 years to 10.9 for site 8C25 and from 10.5 to 11.3 years for site 4194.

The tanks were reported to be 50 years old. Therefore, the conditional probability of a leak given point corrosion would have reached unity approximately 29 years ago. In addition, there is no evidence of hydrocarbons in the soil.

This suggests that a condition of uniform corrosion exists. It is extremely unlikely that leakage could persist for so long a period without detection and without some evidence of ground contamination. A single tank tightness test could confirm this. If the tanks tested tight, uniform corrosion could be assumed with probability one and no further testing would be warranted.

Tables F-2 and F-3 show the Warren Rogers Associates findings at sites 8C25 and 4194, respectively.

Table F-1. Soil Analysis

Site	Sample no.	% Moisture		Conductivity (μmhos/cm)		pH		Sulfides (ppm)		Hydrocarbon
		W. Rogers	NIPER	W. Rogers	NIPER	W. Rogers	NIPER	W. Rogers	NIPER	W. Rogers
4194	1Mid[a]	9.95	9.19	66	66.3	5.6	5.52	0	0	0
	1Bot[b]	9.23	9.79	49	45.5	5.8	5.73	0	0	0
	2Mid	9.27	10.89	57	37.1	5.6	5.19	0	0	1
	2Bot	11.45	10.65	61	36.3	5.7	4.91	0	0	0
	3Mid	9.58	11.24	39	32.6	5.7	5.20	0	0	0
	3Bot	7.58	8.76	47	31.4	5.7	5.10	0	0	0
	4Mid	9.68	9.55	79	62.6	5.4	4.55	0	0	0
	4Bot	8.98	9.01	67	54.6	5.5	4.77	0	0	0
	1S-Mid[c]	10.03	7.93	36	15.7	5.6	4.92	0	0	0
	2S-Bot[d]	7.53	11.86	15	34.4	5.7	4.58	0	0	0
	Dist.1[e]		6.46		48.7		4.56		0	
	Dist.2[f]		7.08		28.9		4.88		0	
8C25	1Mid	9.06	6.84	44	32.6	5.5	4.81	0	0	0
	1Bot	7.28	7.18	41	34.7	5.5	5.07	0	0	0
	2Mid	8.38	9.71	26	28.2	5.2	4.21	0	0	0
	2Bot	8.32	7.67	35	28.6	5.3	4.47	0	0	0
	3Mid	9.22	8.52	56	44.2	5.3	4.57	0	0	0
	3Bot	7.71	7.80	49	39.8	4.8	4.05	0	0	0
	4Mid	8.36	7.39	27	25.0	5.0	4.27	0	0	0
	4Bot	7.23	6.11	27	22.4	5.0	4.45	0	0	0
	1S-Mid[c]	9.30	7.93	28	15.7	5.9	4.92	0	0	0
	2S-Bot[d]	10.84	11.86	25	34.4	5.6	4.58	0	0	0
	Dist.1[e]		6.54		15.0		3.83		0	
	Dist.2[f]		15.98		26.8		3.74		0	

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[a] Middle sample.
[b] Bottom sample.
[c] Composite surface sample at 1 ft depth.
[d] Composite surface sample at 2 ft depth.
[e] Sample taken 50 ft from tank.
[f] Sample taken 100 ft from tank.

Table F-2. Determining the Probability of a Leak, Site 8C25

EPA Washington State Locations

Station ID: Building No. 8C25, Fort Lewis, Tacoma, Washington
Age of oldest tank: 50 years
Mean age: 15 (average)
Years after the mean: 35
Probability now leaking: 1.00
Cathodic protection: No

Probability of leak in	
1 year:	1.00
2 years:	1.00
3 years:	1.00
4 years:	1.00
5 years:	1.00

Hydrocarbons in soil: No
Ground water encountered: No
Active transit system nearby: No
High voltage lines nearby: No
Cathodically protected structures nearby: No

Tank	Size	Year installed	Type	Product	Interior corrosion
1	12,000	1934	Steel	Unleaded	Rough
2	12,000	1934	Steel	Unleaded	Rough

Additional Data

Underground aquifer nearby: No
Basements: No
Sewers: Yes
Utility vault or conduit: No
Potable water source: No
Navigable water way: No
Leak detectors: No
Impact valves: No
Vapor recovery systems: Yes
Lines: Steel
Flexible connectors: No

Table F-3. Determining the Probability of a Leak, Site 4194

EPA Washington State Locations

Station ID: Building No. 4194, Fort Lewis, Tacoma, Washington
Age of oldest tank: 50 years
Mean age: 16 (average)
Years after the mean: 34
Probability now leaking: 1.00
Cathodic protection: No

Probability of leak in	
1 year:	1.00
2 years:	1.00
3 years:	1.00
4 years:	1.00
5 years:	1.00

Hydrocarbons in soil: No
Ground water encountered: No
Active transit system nearby: No
High voltage lines nearby: No
Cathodically protected structures nearby: No

Tank	Size	Year installed	Type	Product	Interior corrosion
1	12,000	1934	Steel	Diesel	Rough
2	12,000	1934	Steel	Regular	Rough

Additional Data

Underground aquifer nearby: No
Basements: No
Sewers: Yes
Utility vault or conduit: No
Potable water source: Yes
Navigable water way: No
Leak detectors: No
Impact valves: No
Vapor recovery systems: No
Lines: Steel
Flexible connectors: No

APPENDIX G

FACILITY DESCRIPTIONS, TANK CHARACTERISTICS, AND TEST CONDITIONS

This appendix presents the descriptions and tank characteristics of the tank systems tested at the five facilities selected for the development study. Specific test conditions are also described for each method tested. Table G-1 lists the tanks or tank systems tested and their characteristics.

I. FACILITY DESCRIPTIONS

A. Damneck Naval Combat Training Center, Virginia Beach, VA

1. Site Description

Testing was conducted by all three test crews at a tank located at the Training Center's Public Works Division where the auto compound and heavy equipment motor pool and service garage were located. The access road to the Public Works Division carried a high volume of traffic, including periodic heavy equipment transportation, throughout the day. The site diagram is shown in Figure G-1.

Just to the east of the access road was a marshy area whose water level fluctuated with the tide. Two product dispensers were on a concrete pad. The tank tested was to the north of the dispensers. The tank was located under a dirt surface. A pit measuring approximately 1 ft x 3 ft x 6 ft had been dug around the test tank's fill pipes.

2. Tank Description

The tank tested was a 5,000-gal (nominal; 5,084 actual) tank measuring approximately 96 in. in diameter and 13 ft 6 in. in length. The age of the tank was 28 years. When the crew arrived, the tank was holding 4,746 gal of regular gasoline. The tank was covered with about 2 ft of soil material. The tank was made of steel and the type of delivery system was suction.

B. Pitstop

1. Site Description

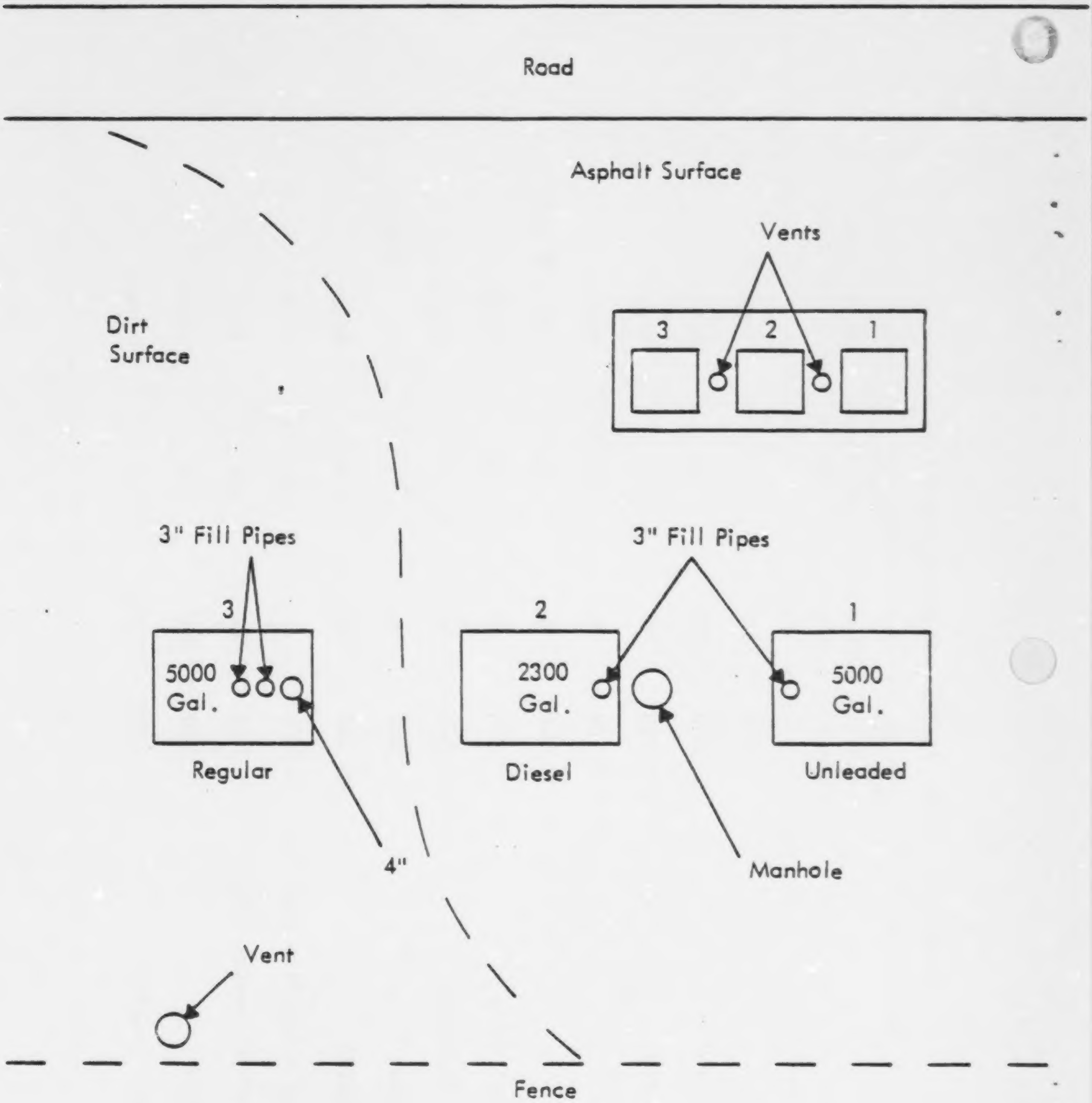
Testing was conducted on two tanks at this site by all three test crews. The site was a convenience store which had a moderate level of business. The site diagram is given in Figure G-2. An oil sheen observed on the surface of the stream that ran adjacent to the property had led to the decision to test at this site.

2. Tank Description

Two tanks were tested, both containing regular gasoline. The manifold connecting the tanks was disconnected prior to testing. The south tank was an 12,000-gal steel tank measuring 108 in. in diameter. Subsequent to testing, the fill pipe connection into the tank was found to be leaking.

Table G-1. Tanks Tested and Their Characteristics

Facility	Tank	Nominal capacity (gal)	Diameter (in.)	Approximate soil cover (in.)	Petroleum product
Damneck	1	5,000	96	24	Mogas
Pitstop	1 (South)	12,000	108	38	Mogas
Pitstop	2 (North)	8,000	96	53	Mogas
Scott	1 (17)	5,000	96	44.5	Mogas
Scott	2 (18)	5,000	96	44.5	No. 2 Diesel
Fort Lewis	1 (8C25 North)	12,000	96	10	Mogas
Fort Lewis	2 (8C25 South)	12,000	96	5	Mogas
Fort Lewis	3 (4194)	12,000	96	22	No. 2 Diesel
Fort Lewis	4 (10E10)	12,000	96	4	Mogas
Langley	1 (Hydrant System Tank 3)	25,000	124	12	JP-4
Langley	2 (Hydrant System Tank 5)	25,000	124	15	JP-4
Langley	3 (Mogas)	10,000	90	20	Mogas
Langley	4 (Golf Course)	1,000	49.5	12	Mogas



All Tanks Are Suction Delivery

Figure G-1. Damneck site diagram.

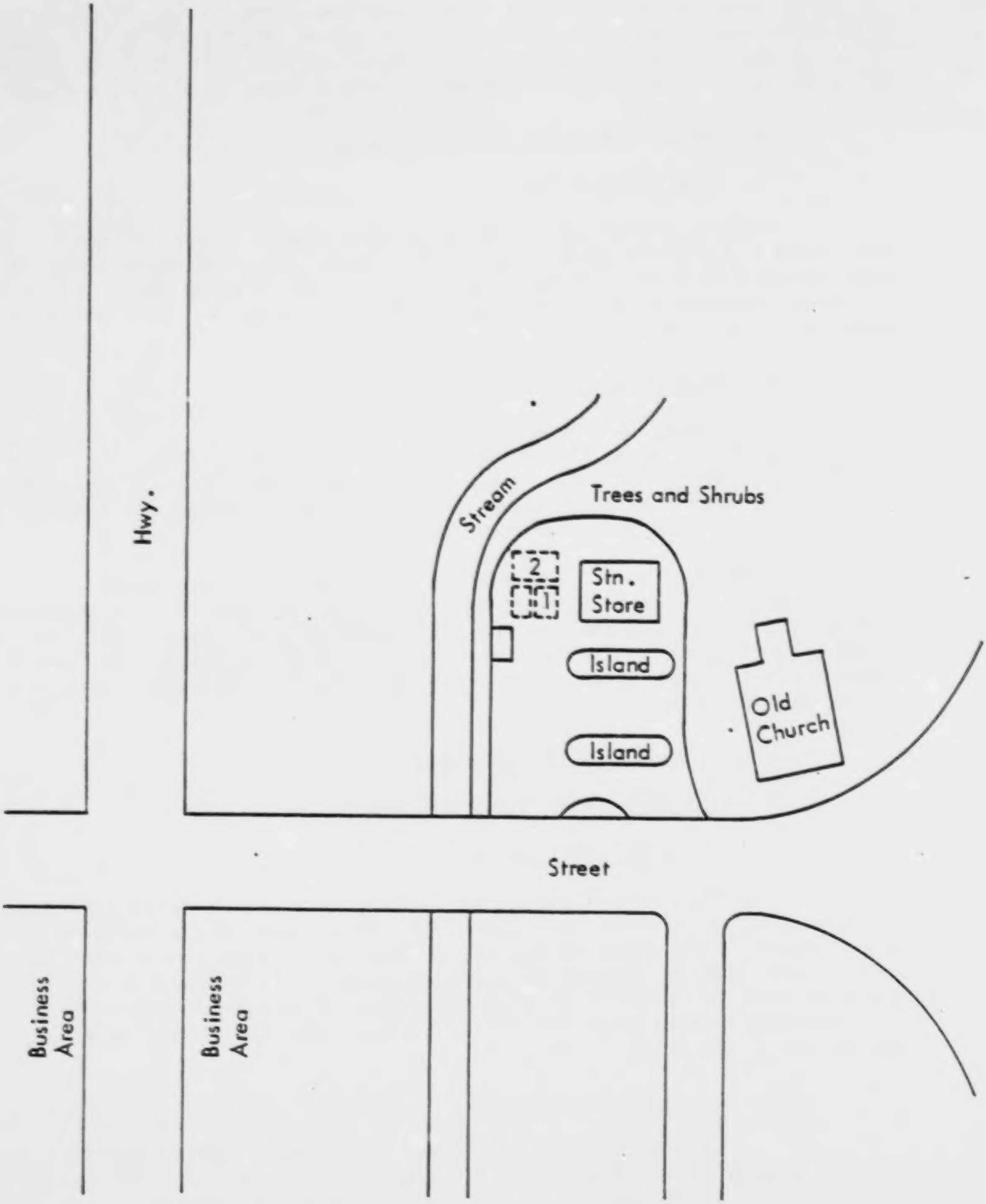


Figure G-2. Pitstop site diagram.

The north tank was an 8,000-gal steel tank measuring 96 in. in diameter. Both tanks contained 4-in. fill pipes. A third, 12,000-gal tank containing unleaded gasoline was not tested. The depth of the soil cover above the tanks was 3 ft. The delivery system for these tanks is a pressure system.

C. Scott Air Force Base, Belleville, IL

1. Site Description

Testing was attempted at this site (Tanks 17 and 18) by all three test crews. A site diagram is given in Figure G-3. The water table in this area varied from 4 to 7 ft below the surface, the average being 4.5 to 5 ft. The tanks received much use during the day, and a nearby road carried a moderate level of traffic.

2. Tank Description

Both tanks, which were approximately 35 years old, had been painted on the outside and epoxy coated on the inside before relocation to this site in 1981. The volume of each tank was 5,000 gal, and each lay under 44.5 in. of soil. Tank 17 contained Mogas, while Tank 18 contained No. 2 diesel fuel. Both tanks have a suction delivery system.

Although none of the engineering drawings showed connections between the two tanks, evidence obtained during testing by Leak Lokator suggested some type of connection between the two. Although this was never verified, if tr it would cast doubt on the test results for these two tanks. Neither of the other two test crews observed any problems, which is difficult to explain for the Petro-Tite test.

D. Fort Lewis Army Base, Tacoma, WA

1. Site 8C25 Tanks North and South

a. Site Description

Testing was conducted at this site by all three test crews. The site diagram is shown in Figure G-4. These tanks appeared to be buried in pea gravel. The depth of the top of the tanks below ground surface was 3 ft. There were no streams or overhead power lines nearby. A lightly traveled road lay about 50 ft from the nearer of the two tanks. Soil coring that had been conducted in the area indicated that the water table was below the bottom of the tanks.

b. Tank Description

Each of the two 12,000-gal steel tanks tested was 96 in. in diameter and 30 ft in length. At the time of the test the tanks contained Mogas and were being used primarily for long term fuel storage. The tanks were 50 years old. The delivery system was a suction pump housed in a nearby shed.

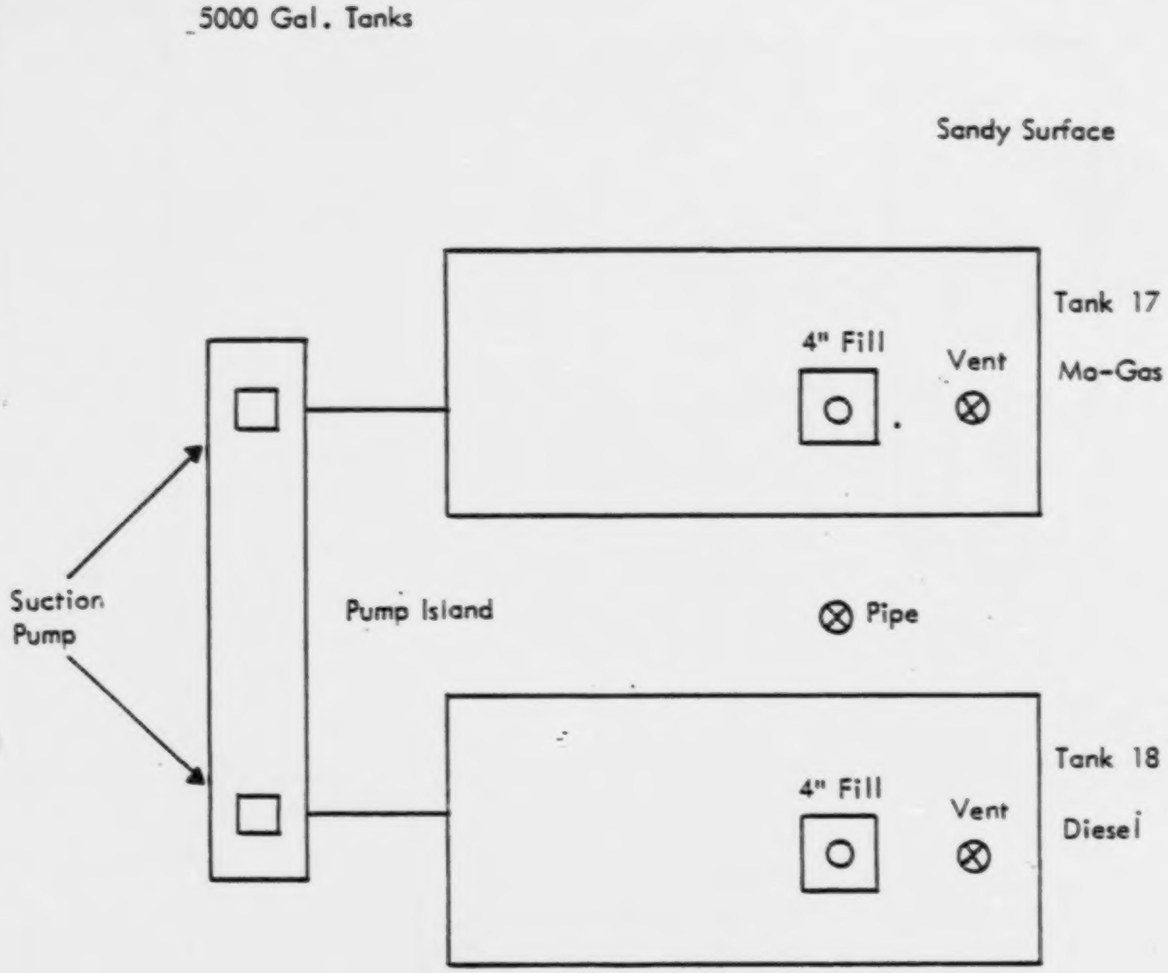


Figure G-3. Scott AFB site diagram.

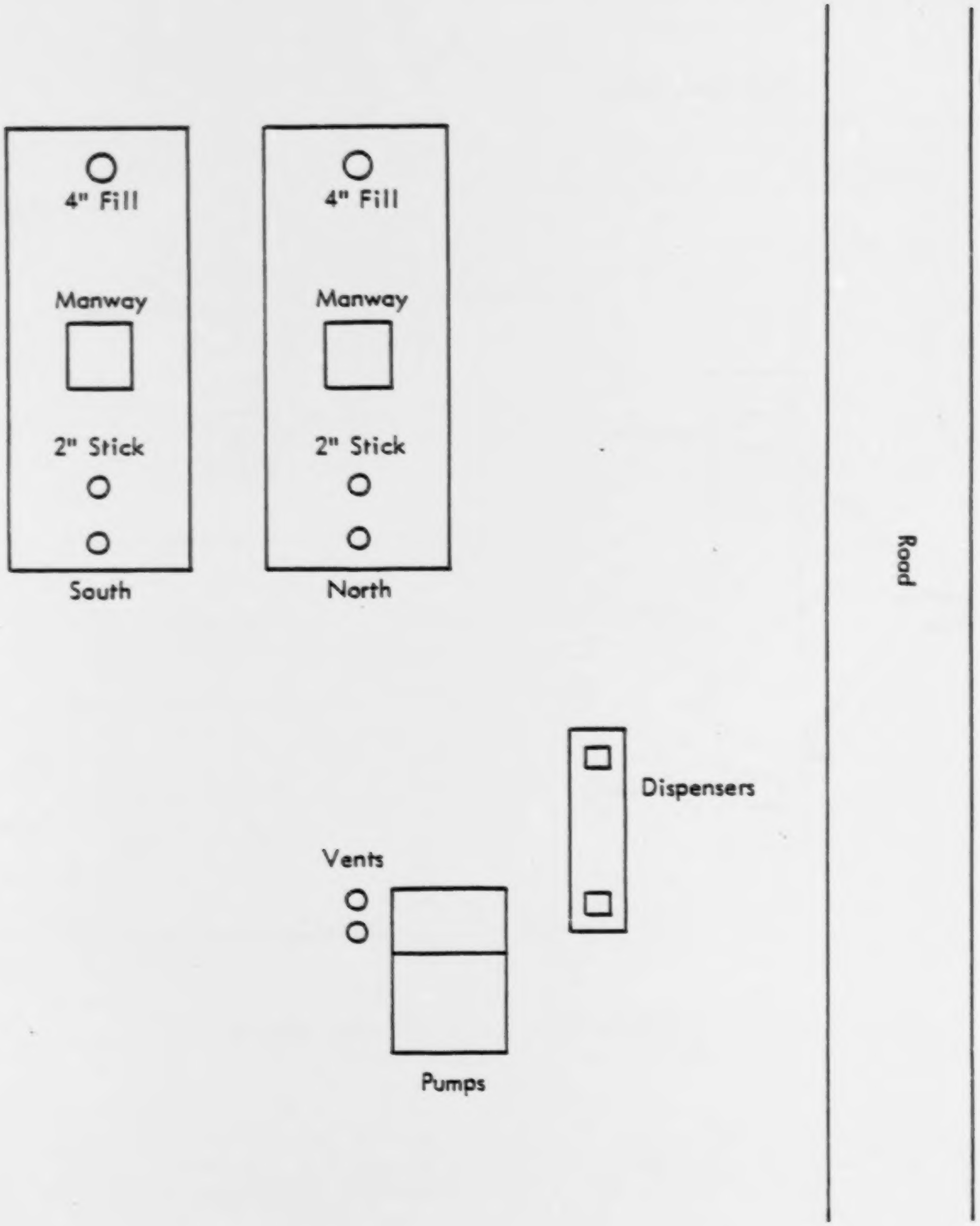


Figure G-4. Fort Lewis site 8C25 diagram.

Openings into each tank consisted of one 4-in. diameter fill pipe with a removable aluminum drop tube located on a 24-in. manway, a 2-in. diameter stick pipe, a second 2-in. opening which was capped, and a 2-in. diameter vent pipe. The approximate soil cover above the north tank was 10 in., and that above the south tank was 5 in.

2. Tank 4194

a. Site Description

Testing was conducted by Leak Lokator and attempted by Petro-Tite at this site. The tank was located at the backup station to the main high volume station across the street. The site diagram is shown in Figure G-5. No streams or overhead power lines were nearby. A heavily traveled four-way stop intersection was within 50 ft of the tank. Soil coring that had been conducted in the area indicated that the water table was below the bottom of the tank.

b. Tank Description

The tank was a 12,000-gal steel tank 96 in. in diameter and 30 ft in length. At the time of the test the tank contained No. 2 diesel fuel. This tank had a level soil cover with the top of the tank 22 in. below grade. The tank was 35 years old. Its delivery system was a suction pump housed in a nearby building. There were two openings into this tank: a 4-in. diameter fill pipe located on a 24-in. manway and a 2-in. diameter vent pipe.

3. Tank 10E10

a. Site Description

Testing was conducted at this site by two of the test crews. The site diagram is shown in Figure G-6. The tank was buried in pea gravel. Built-up earth mounds 24 to 36 in. above the surrounding ground surface covered the tanks. The depth of the top of the tank below ground surface was 2 ft. No streams or overhead power lines were nearby. A lightly traveled road lay approximately 50 ft west of the tank. Soil coring that had been conducted in the area indicated that the water table was below the bottom of the tank.

b. Tank Description

The tank was a 12,000-gal steel tank 96 in. in diameter and 30 ft in length. The tank at the time of the test contained Mogas and was being used primarily for long term fuel storage. The tank was 35 to 50 years old. Its delivery system was a suction pump housed in a nearby building. Openings into this tank consisted of a 2-in. diameter stick hole, a 4-in. diameter fill pipe located on a 24-in. manway, and a 2-in. diameter vent pipe.

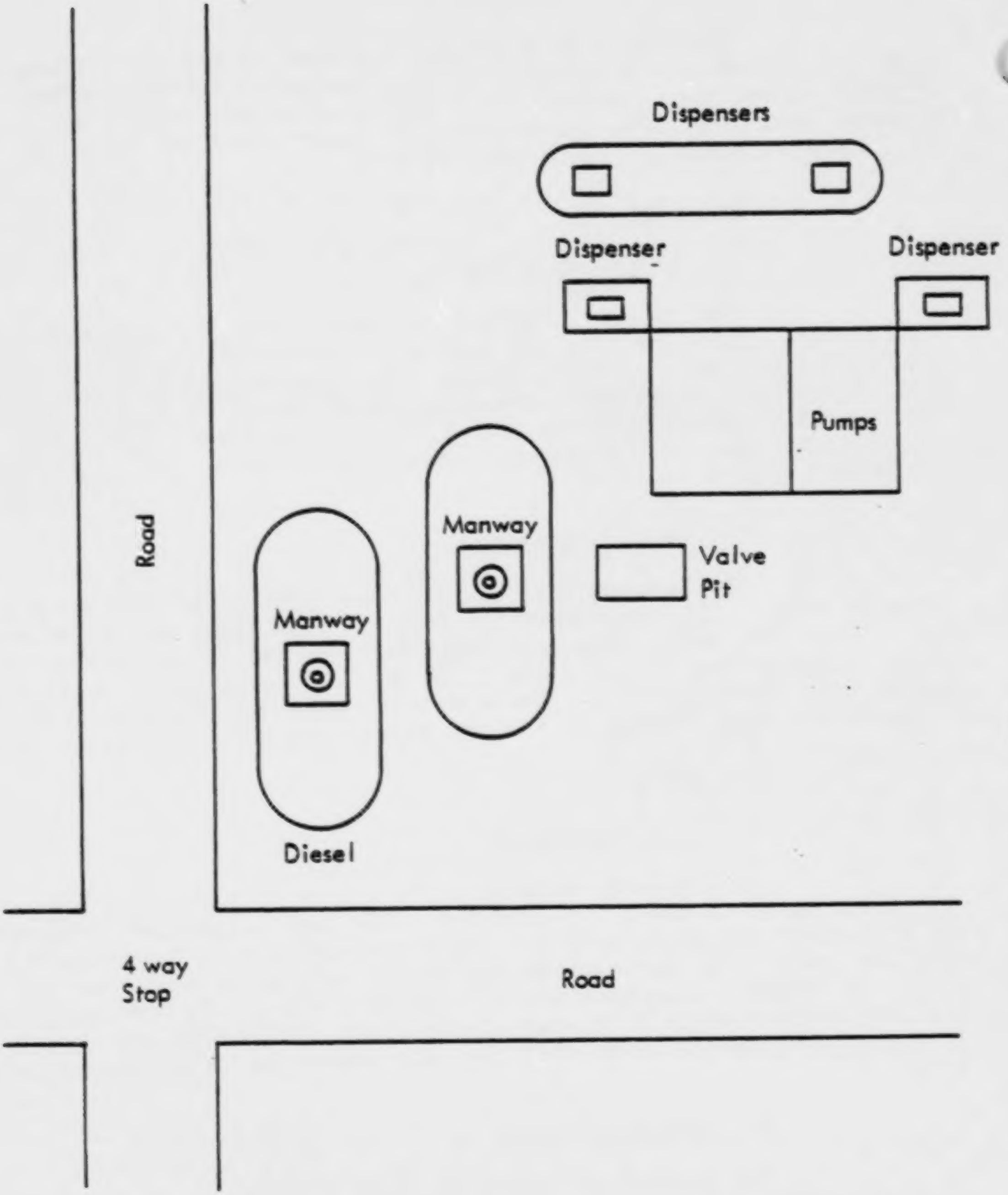


Figure G-5. Fort Lewis tank 4194 site diagram.

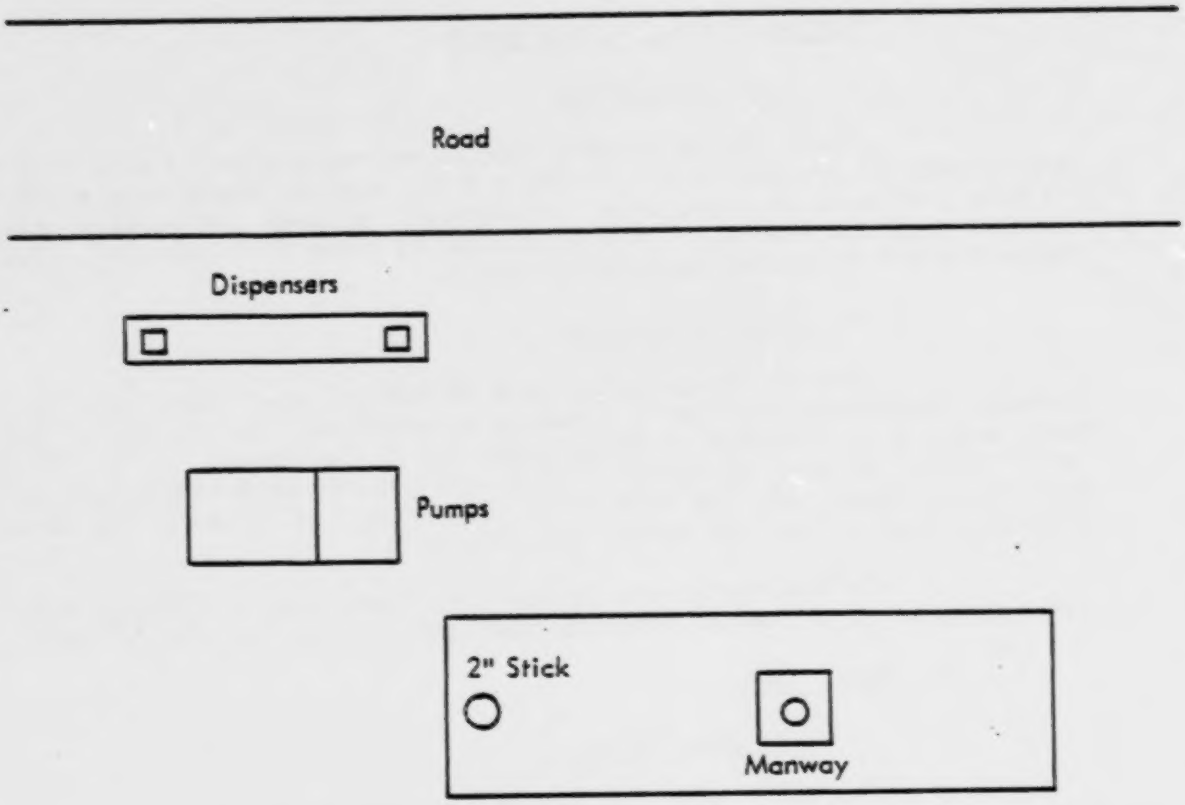


Figure G-6. Fort Lewis tank 10E10 site diagram.

E. Langley Air Force Base, Hampton, VA

Testing was attempted at several locations at Langley Air Force Base, Hampton, Virginia. Testing was conducted by only Petro-Tite at the golf course site, and by only ARCO at the Mogas site. Both Leak Lokator and ARCO attempted to test at the hydrant system site.

1. Hydrant System Tanks 3 and 5

a. Site Description

These two tanks were located approximately 1/4 mile from the main runways of the airfield. At the hydrant complex, there were eight tanks, all with piping to the ramp area. On adjacent roadways and runways, traffic appeared light to moderate. A site diagram is shown in Figure G-7. Two of the test crews attempted tests at this site.

b. Tank Description

The two tanks tested were 25,000-gal steel tanks 124 in. in diameter containing JP-4 fuel. A manway extended down to the top of the tank, and a 4-in. diameter riser extended out of the manway 12 in. The material above the tank was gravel. Some difficulties were encountered in installing equipment into the tank, which suggested that a ladder may have been present extending from the manway into the tank.

It was impossible to overfill these tanks due to the turbine pump system which presented numerous problems with sealing the system.

2. Mogas Tank

a. Site Description

The Mogas tank was located adjacent to the runway. Both vehicle and air traffic nearby appeared light to moderate. The Mogas tank was buried inside a truck compound. Although there was no through traffic, fuel delivery trucks passed by the tank during the testing. This traffic was routed as far as possible around the test tank since one crew was conducting testing at the time. A site diagram is given in Figure G-8.

b. Tank Description

The tank tested was an approximately 10,000-gal fiberglass tank, 1 to 2 years old, whose diameter was about 90 in. The distance from the top of the fill pipe to the top of the tank was 49-1/4 in., and to the bottom of the tank was 139-1/2 in. This tank contained Mogas fuel, and the depth of the soil cover was 20 in. The tank was 1 to 2 years old.

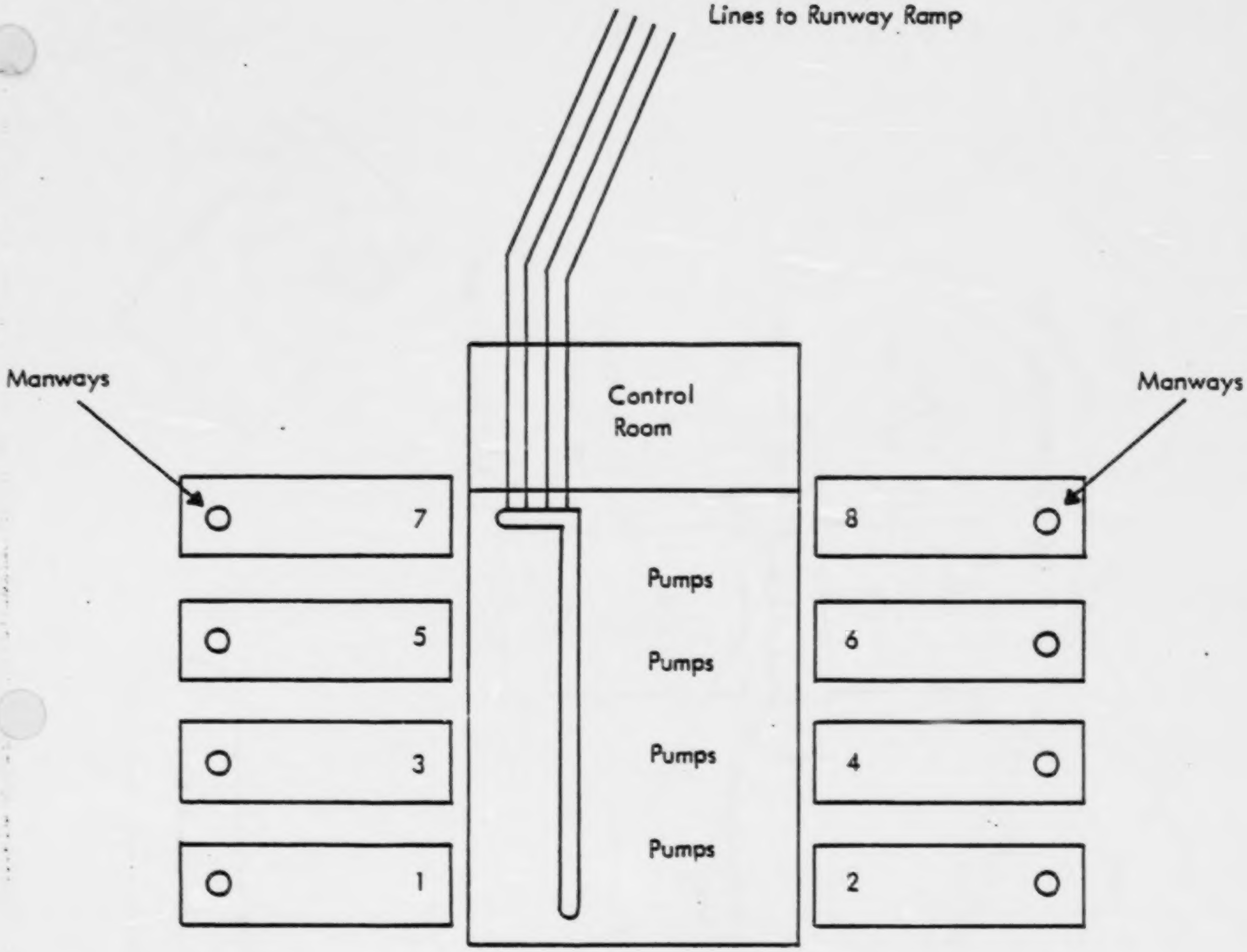


Figure G-7. Langley AFB hydrant system site diagram.

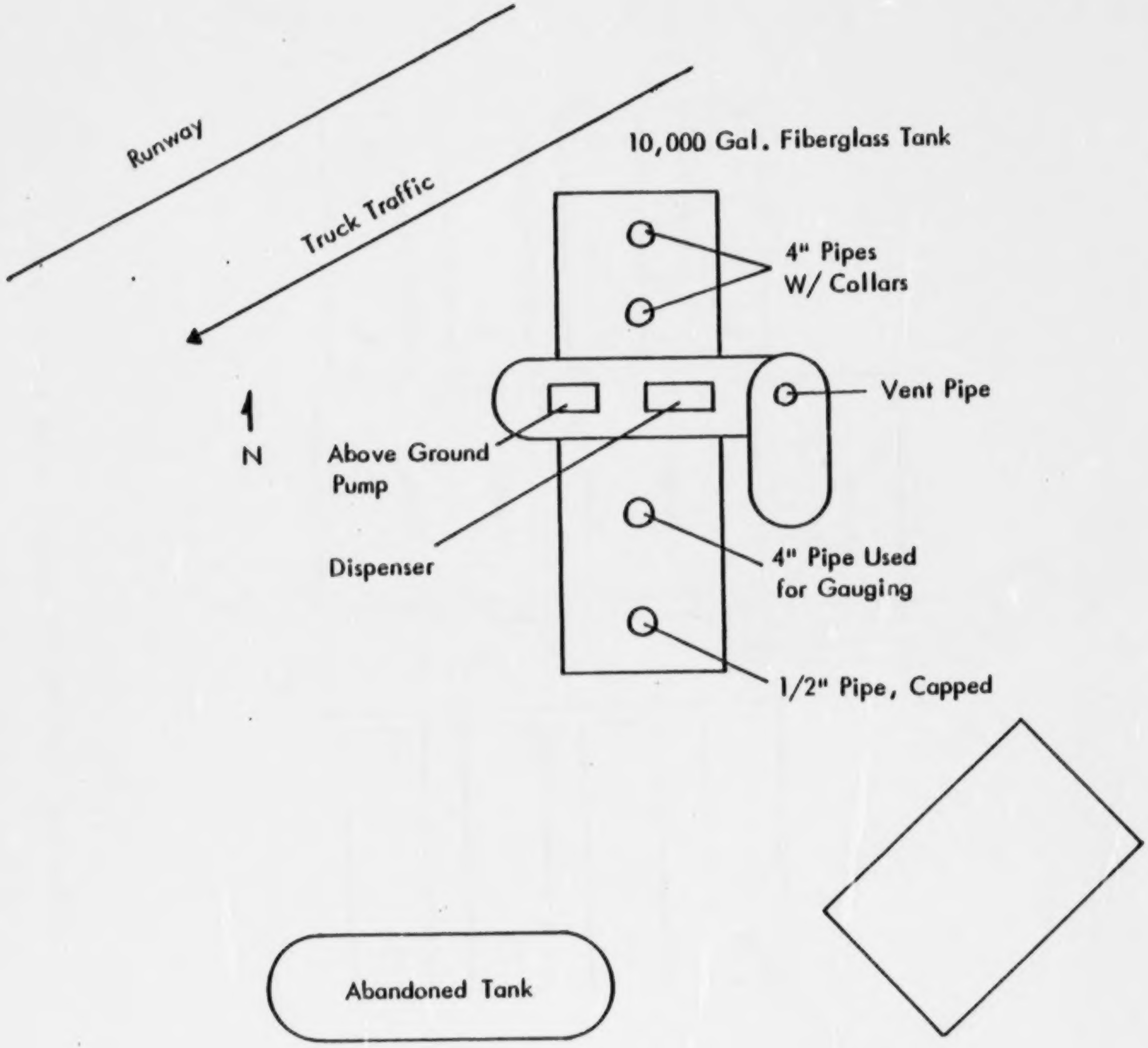


Figure G-8. Langley AFB M[illegible]s tank site diagram.

3. Golf Course Tank

a. Site Description

This tank was located at the base's golf course in a grassy area isolated from vehicular traffic. Some 100 ft to the west of the tank was a small creek. A site diagram is shown in Figure G-9. One test crew tested this tank system.

b. Tank Description

The test tank, which contained Mogas, had approximately 1,000-gal capacity, was 49-1/2 in. in diameter and 10 ft in length, was 8 years old, and was constructed of steel. The tank was buried under a soil cover of about 1 ft. One dispenser was connected to the tank. The delivery system was suction.

II. TEST CONDITIONS

Data specific to each tank tested in the development study are provided in this subsection. A matrix of the tests conducted at each tank is shown in Table G-2.

A. Damneck Naval Combat Training Center

1. ARCO

Tests were attempted over a span of 2 days (October 11-12, 1984). On the first day of testing, the ARCO equipment did not arrive on time. The first day was spent doing temperature profiles and lowering the fuel level to 3,756 gal (73.9% capacity). On the second day, the ARCO test crew was unable to get its equipment to operate properly and could not get a baseline. Eventually, testing was called off (after 18 h). Weather conditions were clear and breezy. Ambient, surface, and tank temperatures were recorded both days but could not be used because no testing was conducted. Wind and vibrations appeared to cause the most problems for the ARCO test.

2. Leak Lokator

On the first of this 2-day test (September 20-21, 1984), the test crew arrived at the site at 7:45 a.m. Testing did not begin until noon, however, because approximately 2 h was spent on setting up equipment and the rest of the time spent was related to fuel (topping off) delays. The first day's test was run from 12:45 to 3:00 p.m. at a sample rate (simulated leak rate) of 0.09 gal/h. Samples were taken at 15-min intervals during this period. During the 12:45-1:00 p.m. "calibration pump priming," thermal shutoff on the pump shut down. The pump was restarted in about 15 s. The test company (Hunter Environmental) claimed this "messed up" its run. During testing, ambient temperatures ranged from 81° to 85°F, and surface temperatures ranged from 69° to 72°F. The tank temperature (from a thermistor placed at 7-ft depth) stayed at 73.64° to 73.65°F.

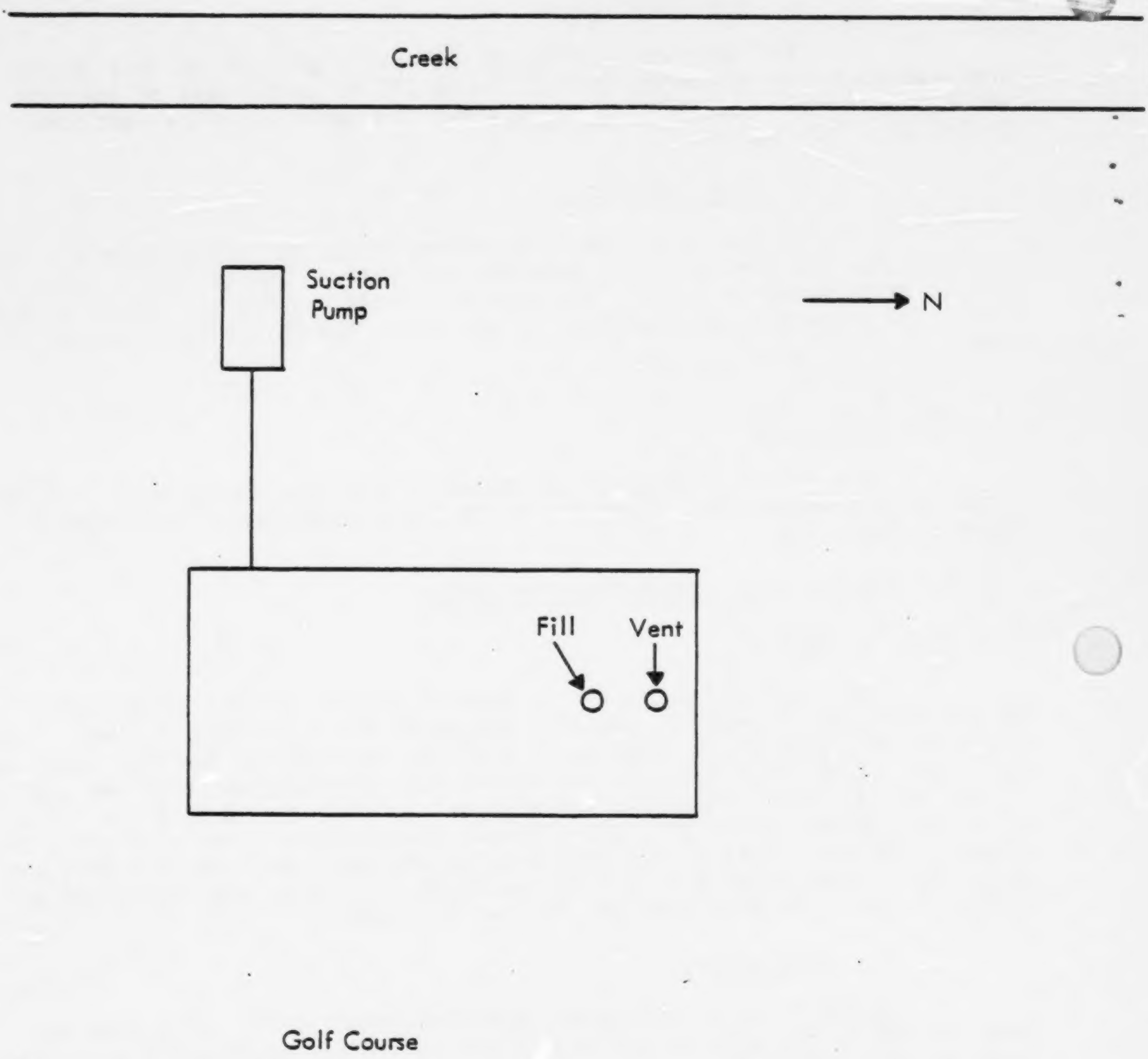


Figure G-9. Langley AFB golf course site diagram.

Table G-2. Matrix of Tests Conducted

Facility	Tank	ARCO	Leak Lokator	Petro-Tite
Damneck	1	T[a]	T	T
Pitstop				
South		T	T: Noisy (vibration), possible vapor	T
North		T	T	T
Scott				
17	1	Out of time	T	T
18	2	T	T: Manifold (?)	T
Fort Lewis				
8C25 north	1	T	T: Leak at about gasket; couldn't test	--
8C25 south	2	T	T	T
4194	3	--	T: Poor sensitivity (-0.171)	Added 400 gal; couldn't fill up (bad leak?)
10E10	4	--	T: Results questionable	T
Langley				
HS tank 3	1	--[b]	T: Multiple leaks, plumbing problem	Would have had similar problems if testing had been attempted
HS tank 5	2	Tried, but couldn't test	T: Plumbing problems	Would have had similar problems if testing had been attempted
Mogas	3	T	--	--
Golf course	4	--	--	T

[a] Letter T indicates the tank or tank system was tested.
[b] Dash (--) indicates testing was not conducted.

During the second day of testing, tests were conducted at two different leak rates, each for 1 h 45 min. Ambient temperatures during this day's tests ranged from 76° to 78°F with surface temperatures ranging from 70.64° to 74.43°F. A thermistor was again placed into the tank at 7 ft (from the top of the fill pipe), and during testing, tank temperatures were 73.32° to 73.33°F. The weather was clear (no barometric pressure data were collected). Hunter Environmental had some problems while MRI changed the simulated leak rates and in achieving a stable baseline due to product constantly being removed from the tank.

3. Petro-Tite

The test was conducted on October 4, 1984, by O. H. Materials. Prior to testing, a bore hole was dug by the test crew to determine the water table. The water table was determined to be 6 ft below grade; therefore, the test crew erected the standpipe up 99 in. to compensate for the water table. The crew began setup of equipment at 10:00 a.m. with the actual test starting at 1:45 p.m. Testing appeared to go smoothly; the initial simulated leak test was begun at 3:00 p.m. Three 1-h simulated leak rates were conducted. Temperature profiles before and after testing were fairly stable. Ambient temperatures during testing ranged from 64° to 76°F, with surface temperatures from 66.3° to 66.9°F.

B. Pitstop

1. ARCO

The Pitstop north tank was tested on October 4, 1984, starting at 10:00 a.m., and the Pitstop south tank was tested on October 5, 1984, starting at 10:00 a.m. For both tests the fuel level had been adjusted to approximately three-fourths full the day before. Weather conditions during the tests were partly cloudy to clear on October 4 and clear on October 5. Wind in the morning of the first day caused some noise on the sensor. No particular problems were noted during the testing.

2. Leak Lokator

Testing was conducted on the north tank on October 8, 1984. Testing started at approximately 11:00 a.m. Fuel had been delivered the night before. During testing in the morning the weather was still heavily overcast after considerable rain had fallen during the prior two days. By the afternoon of the test the sky had cleared. The testing was conducted routinely and no problems were encountered.

Testing was conducted on the Pitstop south tank on October 9, 1984, starting at 9:00 a.m. Fuel had been delivered to the tank the morning before so that approximately 24 h of stabilization could take place. The sky was overcast during the test, and temperatures were in the low to mid-60s. Two problems were encountered during the test which led to uncertainty in the test results. First, there appeared to be a vapor pocket in the system which could not be readily removed. Second, traffic through the station created vibration which affected the test quality. It was apparent, however, that the tank had a leak.

3. Petro-Tite

Petro-Tite conducted testing at Pitstop on September 13 and 14, 1984, for the north and south tanks, respectively. The north tank was filled on September 13 and the south tank was filled on September 14. The water table was found to be below the bottom of the tank. During testing the weather was mild and sunny. Petro-Tite encountered no difficulties in testing either tank.

C. Scott Air Force Base

1. ARCO

Of Scott Air Force Base tanks 17 and 18, ARCO tested only tank 18 (diesel). On the test days (October 1 and 2, 1984) the weather conditions were clear and sunny with no wind. Because of the amount of difficulty in setting up the test equipment, there was no time to test tank 17. Some vibration problems were observed when aircraft took off in the area.

2. Leak Lokator

Testing was conducted October 11, 1984, on the Mogas tank, and October 12 on the diesel tank. Weather conditions on both days were heavily overcast, and some rain fell on the second day.

During the testing of tank 17 (Mogas), leaking around a manway gasket was observed. An attempt was made to stop the leak, but this was unsuccessful, and the test continued. During the testing of tank 18 (diesel), some interactive effects between the two tanks were noted which gave a strong indication of manifolding between the two tanks. The presence of a manifold could not be confirmed, but connections of some type between the two tanks seem highly probable. As a result, the test results at Scott are highly questionable.

3. Petro-Tite

Testing was conducted on tank 18 on September 18, 1984, and on tank 17 on September 19.

a. Tank 18, Diesel

The test crew arrived at the site at 7:45 a.m. The ambient temperature was 57°F. At 9:00 a.m. Petro-Tite measured the water table at 96 in. The level of fuel in the drop tube was measured to be higher than the actual fuel level in the tank. Petro-Tite needed extra time to set up equipment on the tank, which required removing the manway cover and disconnecting many pipe connections from the cover. A second delay before testing could begin was the topping off of the diesel tank, with 916 gal. delivered within a temperature range of 58° to 65°F at 3:15 p.m. The weather was clear and sunny and the temperature at 3:30 p.m. was 75°F.

Only two leak simulation tests were conducted for this day. The average ambient and surface temperatures during these tests were 55° and 72°F, respectively.

b. Tank 17, Mogas

The test crew arrived at the site at 7:45 a.m. Even though Petro-Tite had modified the manway cover for this tank the previous night, delays were encountered. Obtaining fuel to top off the tank just prior to testing was necessary. The skies were clear and at 1:15 p.m. the ambient temperature was 84°F and the surface temperature was 72°F. Four leak simulation tests, each 85 min in length, were conducted.

D. Fort Lewis Army Base

1. Tanks 8C25 North and South

a. ARCO

Fuel was delivered to a partially full tank on September 17, 1984. ARCO tested the north tank on September 18 and 19 and the south tank on September 19 and 21. Testing began at around 10:00 a.m. with temperature profiles being conducted first. The test crew began setup at approximately 10:00 a.m. and actual testing started at 12:00 p.m. Testing was conducted for approximately 6.5 h. Baseline testing took 5 h and simulated leaks were conducted for a total of 8 h for both days. During the testing the temperatures were mild (70°-80°F) with only light breezes. Very little vehicle traffic was observed during the test, and there did not appear to be any vibration problems. Some problems were encountered in obtaining smooth traces during the early phase of the testing. The cause of the fluctuations was not clear. Otherwise, there is no reason to question the validity of the test results.

b. Leak Lokator

Leak Lokator transferred product from the south tank to the north tank on October 2, 1984, and the manway gasket began leaking, causing the test on this tank to be cancelled. Product was transferred back to the south tank and again the gasket leaked. The gasket was removed and replaced with a new one on the south tank. The tank was filled on October 3 for testing. Testing began at around 8:30 a.m. after a temperature profile was conducted. The test crew began setting up at approximately 8:30 a.m. and the actual test started at 12:00 p.m. Testing was conducted for approximately 5.5 h. Baseline testing took 1 h while simulated leaks were conducted for 4.5 h. The temperature was mild (60°-70°F) with a light breeze. Very little traffic was observed during the test, and there did not appear to be any vibration problem. The only problems encountered were the leaking gaskets, and these were repaired on the tank which was tested. There is no reason to question the validity of the test results.

c. Petro-Tite

Petro-Tite did not attempt to test the 8C25 north tank because of the gasket problem discovered by Leak Lokator. Fuel was transferred into the south tank on October 9, 1984, in order to conduct the test. Testing began around 8:30 a.m. with a temperature profile being conducted first. The test crew began setup at approximately 8:15 a.m. and the actual test started at 1:00 p.m. Testing was conducted for approximately 4.5 h. Baseline testing took 4 h, while simulated leak testing was conducted for 0.5 h. During the testing the temperature was approximately 60°F. Light rain began to fall at 1:00 p.m. Wind was 5 to 10 mph during the day. Very little traffic was observed during the test. A leaky cap on the manway 4-in. pipe postponed the start time by 2.5 h. The baseline test was conducted with no problems. Shortly after the simulated leak test started, the base's electrical power went out and the simulation test had to be terminated.

2. Tank 4194

a. Leak Lokator

Fuel was delivered on October 3, 1984, to fill the tank, and the tank was topped off on October 4. Leak Lokator tested the tank on October 4. Testing began at around 12:15 p.m. with a temperature profile being conducted first. The test crew began setup at approximately 11:00 a.m. and actual testing started at 1:30 p.m. Testing was conducted for approximately 6 h. Baseline testing took 1 h and simulated tests were conducted for 5 h. During the testing the temperature was about 60°F. The sky was cloudy and there was a light breeze. It rained all morning. There was heavy traffic all day. Leak Lokator had some problem achieving good sensitivity with its equipment. The cause of this is unclear. Otherwise, there is no reason to question the validity of the test results.

b. Petro-Tite

The tank needed to be topped off on October 10, 1984, due to delivery October 3. Petro-Tite arrived at 7:30 a.m. and conducted a temperature profile first. The test crew began setup at approximtely 8:30 a.m., but the actual test never started. On the test day the weather was cold and rainy (55° to 60°F) and there was a light breeze. It rained off and on all day. Over 400 gal of product were added to the tank with no success in filling the tank or in putting a head pressure on it. Piping was dug up and no visible leaks were observed. It is suspected that the tank was slanted and an air pocket could not escape within the 3-in. piping that led from the tank to the pump.

3. Tank 10E10

a. Leak Lokator

Fuel was delivered October 3, 1984, to fill the tank. The tank was tested on October 5. Testing began at around 8:30 a.m. with a temperature profile being conducted first. The test crew began setup at 8:30 a.m. and the actual test started at 10:15 a.m. Testing was conducted for approximately 6 h. Baseline testing took 1 h and simulated leaks were conducted for 5 h. During the testing, the temperature was mild (about 60°F) and there was a light breeze. Some traffic passed by but not enough to cause vibration problems. No observable problems were encountered during the testing. The data became questionable once the results were received from Leak Lokator. After analyzing the data, no explanation of what happened could be found. The data without temperature compensation compared better with the simulated rates than the temperature-compensated data.

b. Petro-Tite

Fuel was delivered on October 3, 1984. The fuel level was not lowered after Leak Lokator had tested the tank. Petro-Tite tested the tank on October 11. Testing began at around 8:30 a.m. with temperature profiles being conducted first. The test crew began setup at approximately 9:00 a.m. and the actual test started at 10:15 a.m. Testing was conducted for approximately 8.5 h. Baseline testing took 4.5 h and simulated leaks were conducted for 4 h. The temperature was mild (about 60°F) and there was a light breeze during the testing. Some light traffic was observed but it caused no interference with the testing. The test crew experienced a problem with the sensor box during the test. They installed a new battery but there was still a problem every third or fourth 15-min reading. Because of this, the reported results differ more from the simulated rates than at the previous test sites.

E. Langley Air Force Base

1. Hydrant System Tanks 3 and 5 (Leak Lokator)

Testing at Tanks 3 and 5 at the hydrant complex spanned 2 days. On testing tank 3 on September 22, 1984, leaks were encountered on above-ground plumbing and pump seals. The fuel level was lowered to avoid this, and testing proceeded with few problems. During testing of tank 5 on September 23, the test crew had problems throughout the day primarily with apparent air pockets. Several attempts were made to bleed the air out of the piping. On tank 5, the test crew informed MRI that the tank was losing 3 gal/h at the start of the test.

During both days of testing, the weather was clear and sunny, with a very slight breeze. Ambient temperatures remained in the 70s to 80s with no drastic changes, and ground temperature fluctuated by about 2° to 3°F. Tank temperature (with thermistor placed at 12 ft) remained stable both days. The tank system was a complex one to test because of the excessive and unknown piping. The on-site military personnel were to have "isolated" the tank from the rest of the system, but on tank 5 that was questionable.

2. Mogas Tank (ARCO)

Original efforts were to test tanks 3 and 5, but complications prevented this and the Mogas site was selected instead. ARCO experienced problems achieving a good baseline but testing did begin in the late afternoon. A total of four simulated leak rates were completed. The fill pipes were recessed below ground level and water had to be pumped out about every 10 to 15 min during testing. Weather conditions were clear to partly cloudy with some breeze. Ambient temperatures during testing ranged from 73° to 84°F while the tank temperature remained stable (one probe at 9 ft). The wind appeared to cause a lot of problems with the testing.

3. Golf Course (Petro-Tite)

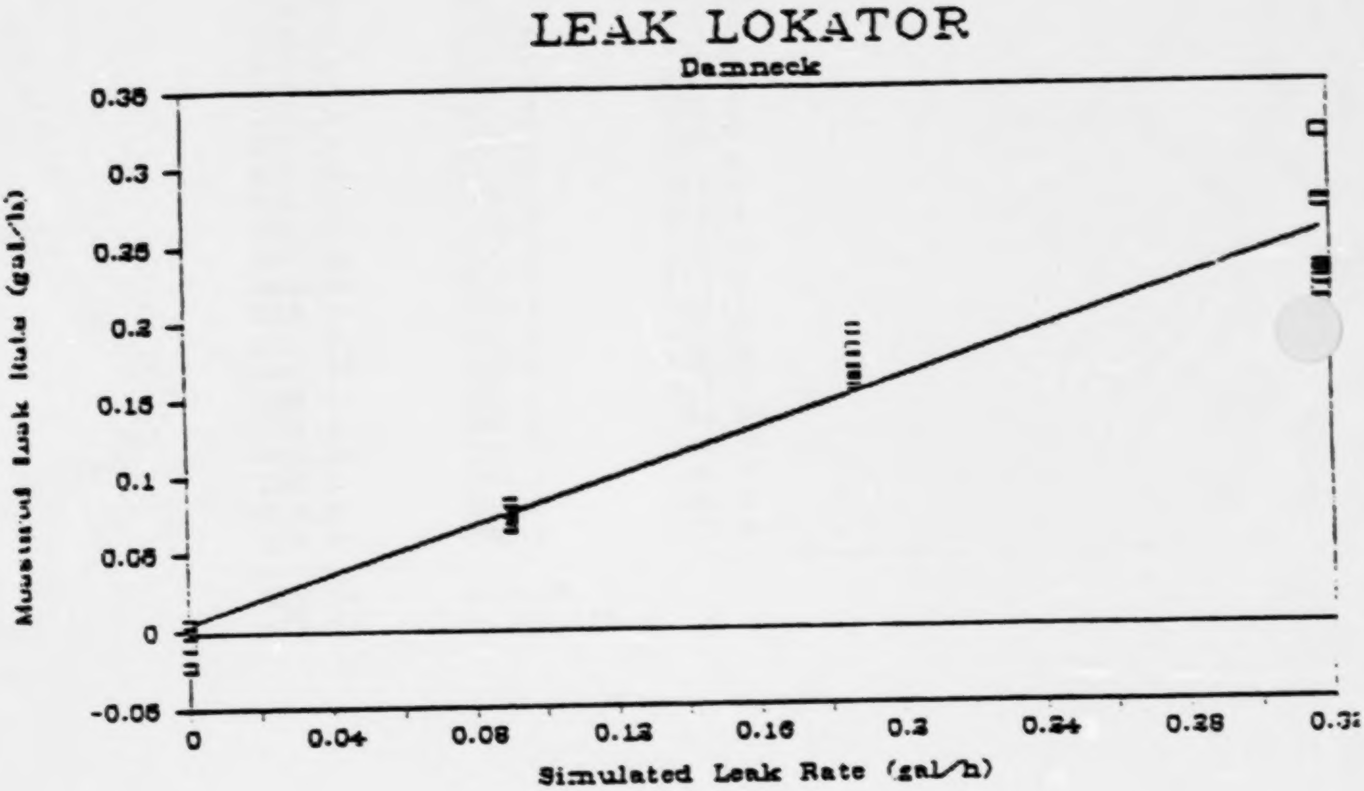
Petro-Tite attempted to test the golf course tank on October 5, 1984. One day of testing was spent on the tank, and eventually the test had to be called off because of a large leak in the tank. When the first pressure head was established, a large pool of fuel appeared on the ground surface. When the soil was removed to expose the top of the tank, the suction line to the dispenser was found to be partially detached (at an elbow joint). The line was disconnected and the tank was capped to isolate it. The final pressure head was established and the leak exceeded 2-1/2 gal/h, with no visible leaks, so the test was called off. The water table was determined to be about 5 ft below the ground surface. Ambient temperatures and weather conditions were not a factor because testing had to be aborted.

APPENDIX H

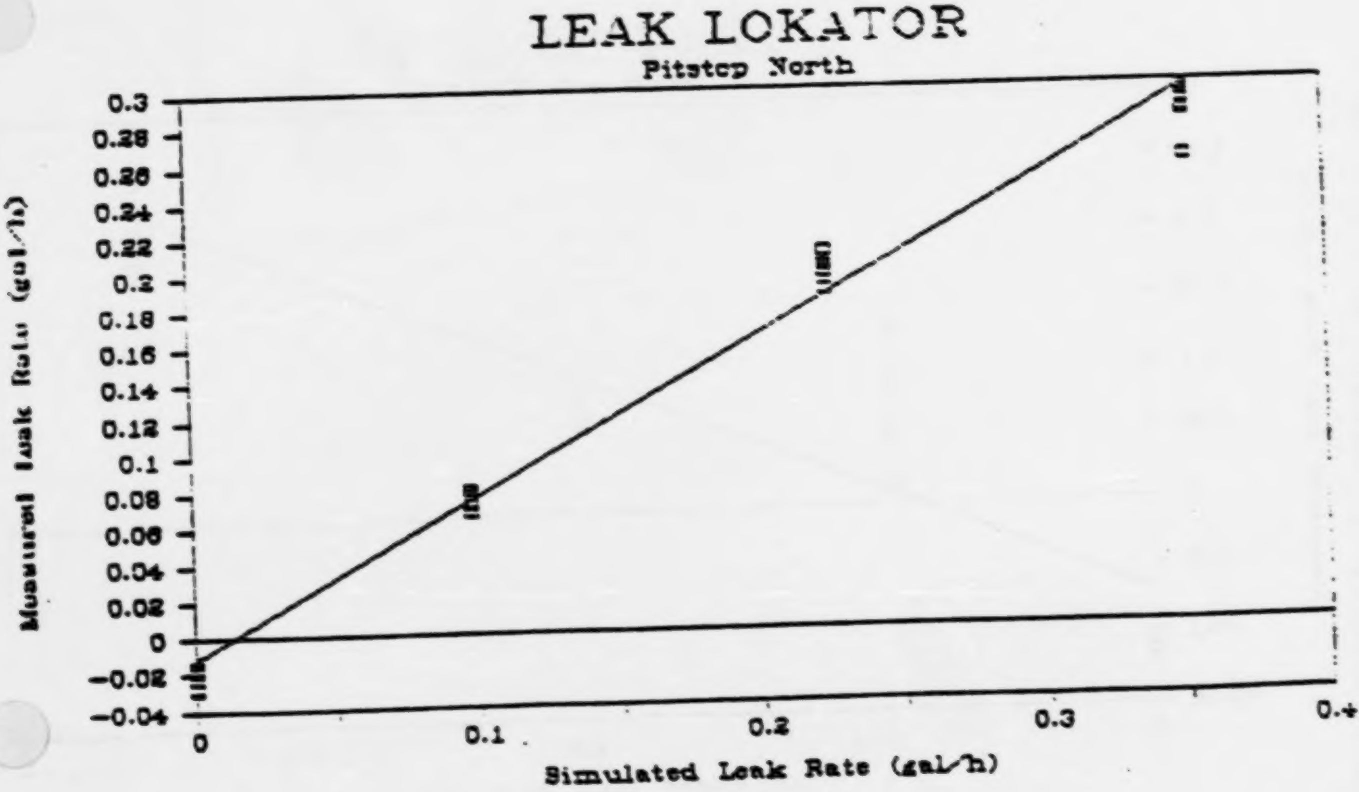
DEVELOPMENT STUDY TEST DATA

LEAK LOKATOR SIMULATION DATA

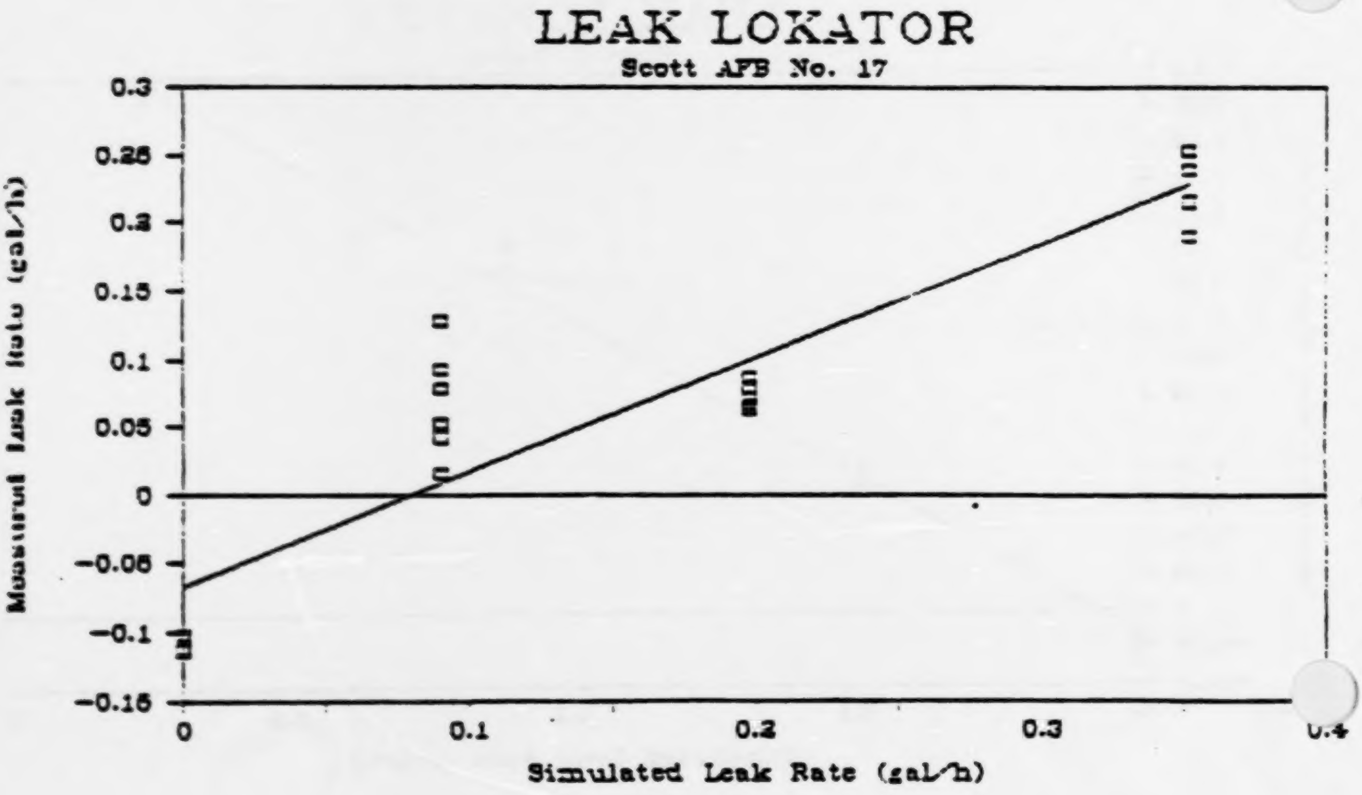
```
      TEST                 RATE      SIM RATE   BASE RATE
-----------------------------------------------------------
LLKRDNMK.SAS;1            0.073       0.090      -0.017
DAMNECK                   0.082       0.090      -0.008
                          0.066       0.090      -0.024
M=.786, Y'=0.005          0.077       0.090      -0.013
                          0.068       0.090      -0.022
                          0.077       0.090      -0.013
                          0.071       0.090      -0.019
                          0.075       0.090      -0.015
                          0.160       0.187      -0.027
                          0.172       0.187      -0.015
                          0.180       0.187      -0.007
                          0.171       0.187      -0.016
                          0.164       0.187      -0.023
                          0.165       0.187      -0.022
                          0.156       0.187      -0.031
                          0.192       0.187       0.005
                          0.171       0.187      -0.016
                          0.317       0.317       0.000
                          0.229       0.317      -0.088
                          0.272       0.317      -0.045
                          0.271       0.317      -0.046
                          0.220       0.317      -0.097
                          0.198       0.317      -0.119
                          0.213       0.317      -0.104
                          0.226       0.317      -0.091
                         -0.001       0.000      -0.001
                         -0.008       0.000      -0.008
                          0.001       0.000       0.001
                          0.005       0.000       0.005
                         -0.023       0.000      -0.023
-----------------------------------------------------------
                                     Mean =      -0.030
                                  Std Dev =       0.034
```


LEAK LOKATOR
Damneck
Measured Leak Rate (gal/h)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
0.04
0.08
0.12
0.16
0.2
0.24
0.28
0.32
Simulated Leak Rate (gal/h)

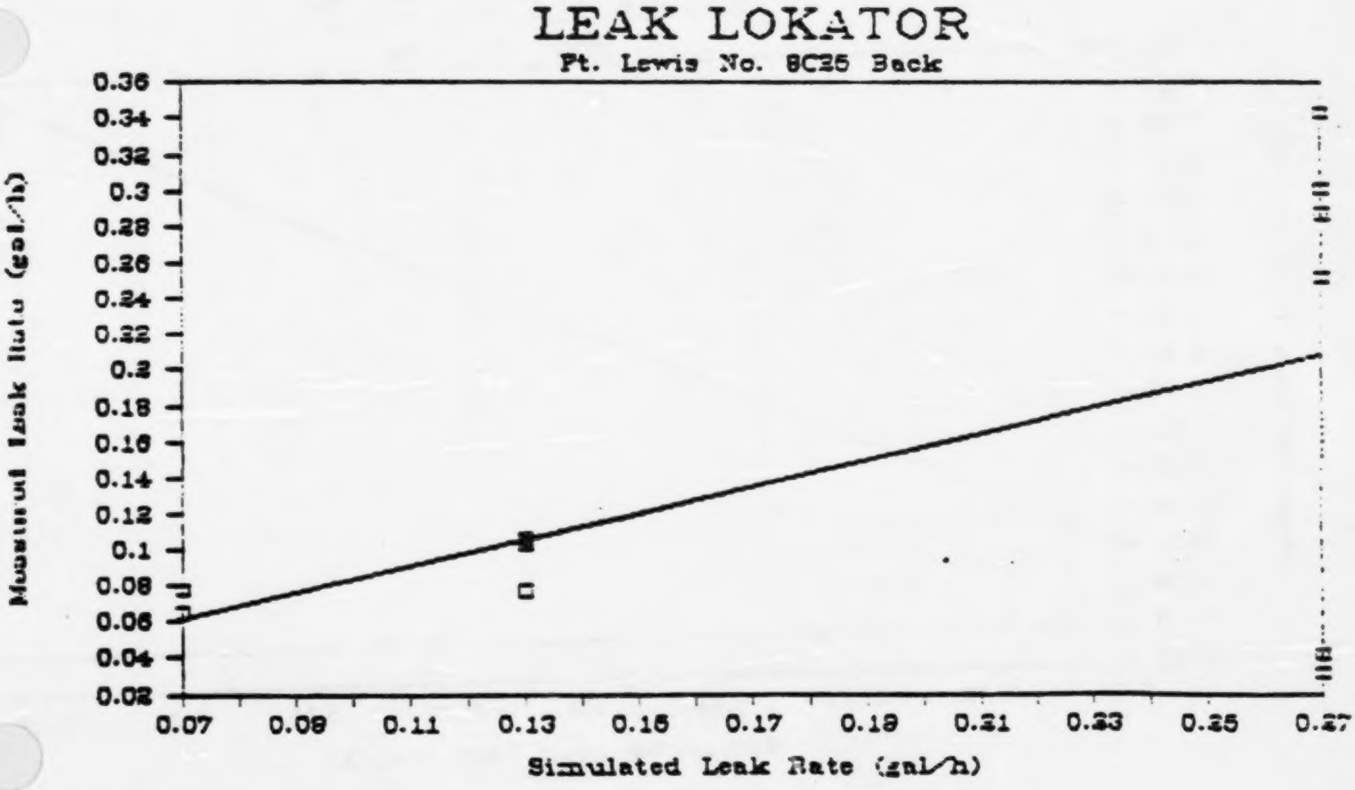
```
        TEST                 RATE       SIM RATE   BASE RATE
------------------------------------------------------------
LOKLEAK.SAS;4               0.289        0.351      -0.062
PITSTOP NORTH               0.283        0.351      -0.068
                            0.285        0.351      -0.066
M=.882, Y'=-0.012           0.297        0.351      -0.054
                            0.294        0.351      -0.057
                            0.258        0.351      -0.093
                            0.289        0.351      -0.062
                            0.068        0.098      -0.030
                            0.072        0.098      -0.026
                            0.080        0.098      -0.018
                            0.077        0.098      -0.021
                            0.209        0.224      -0.015
                            0.188        0.224      -0.036
                            0.198        0.224      -0.026
                            0.209        0.224      -0.015
                            0.201        0.224      -0.023
                            0.197        0.224      -0.027
                           -0.028        0.000      -0.028
                           -0.027        0.000      -0.027
                           -0.022        0.000      -0.022
                           -0.018        0.000      -0.018
------------------------------------------------------------
                                       Mean =       -0.038
                                    Std Dev =        0.022
```



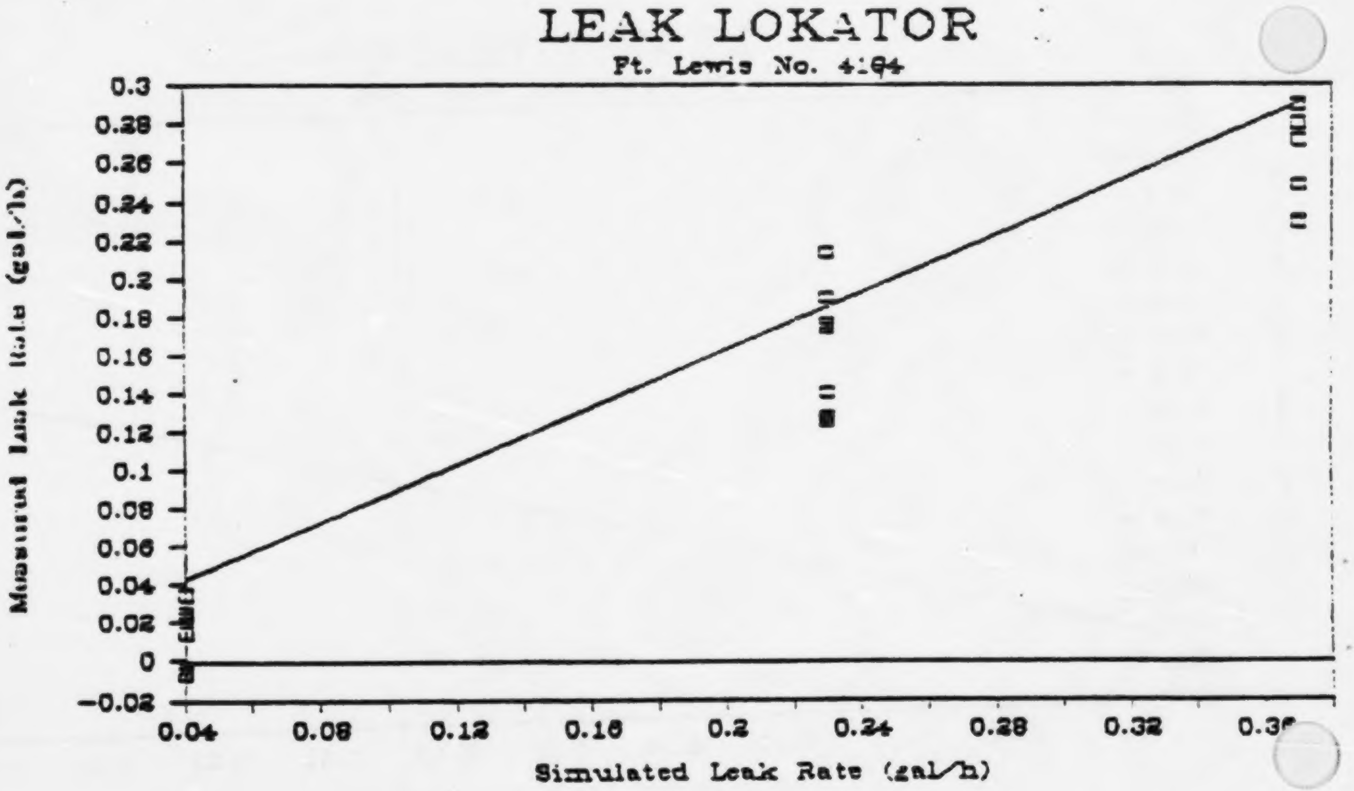
TEST	RATE	SIM RATE	BASE RATE
LLSCT.SAS;1	0.127	0.090	0.037
SCOTT #17	0.043	0.090	-0.047
	0.078	0.090	-0.012
M=.839, Y'=-0.067	0.092	0.090	0.002
	0.016	0.090	-0.074
	0.052	0.090	-0.038
	-0.104	0.000	-0.104
	-0.102	0.000	-0.102
	-0.113	0.000	-0.113
	-0.111	0.000	-0.111
	-0.112	0.000	-0.112
	0.239	0.352	-0.113
	0.190	0.352	-0.162
	0.216	0.352	-0.136
	0.254	0.352	-0.098
	0.066	0.198	-0.132
	0.087	0.198	-0.111
	0.063	0.198	-0.135
	0.079	0.198	-0.119
	0.087	0.198	-0.111
	0.071	0.198	-0.127
		Mean =	-0.091
		Std Dev =	0.050



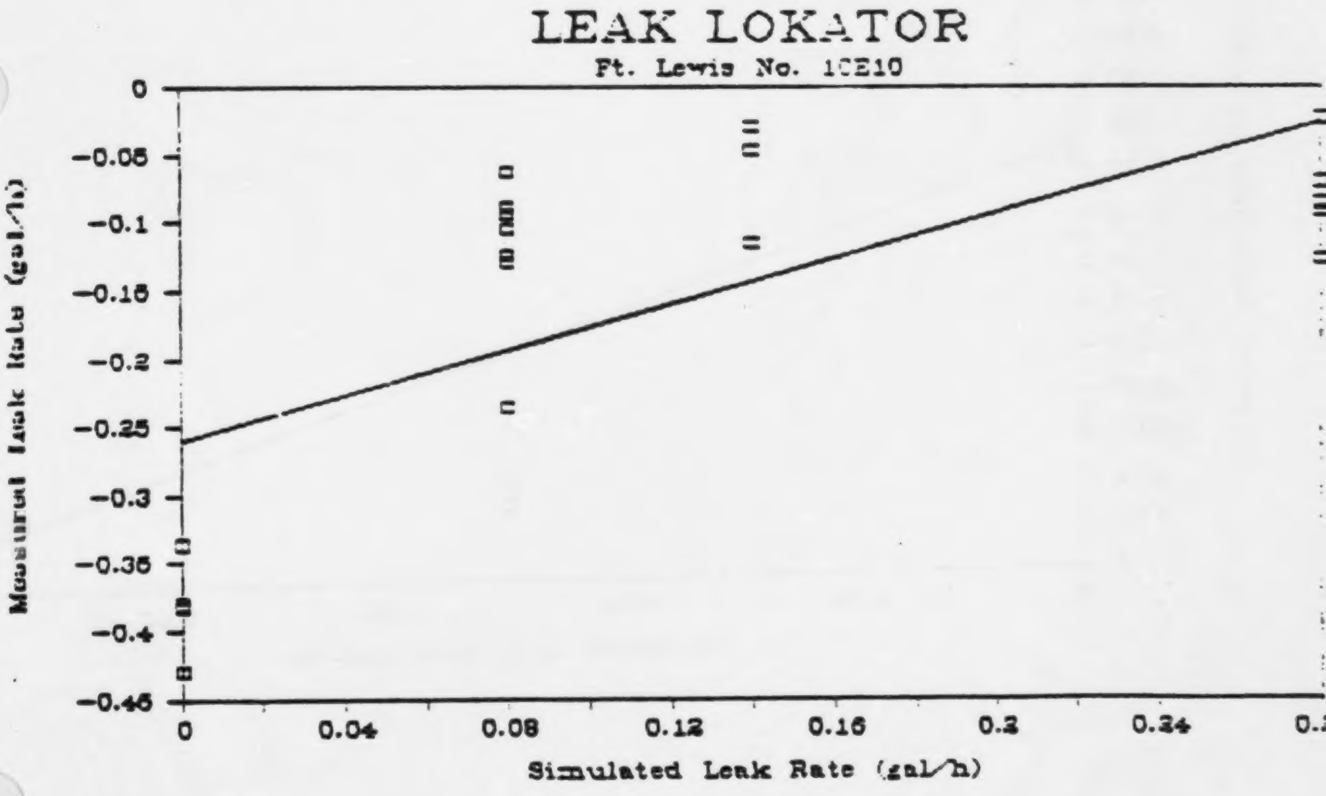
TEST	RATE	SIM RATE	BASE RATE
LOKLEAK.SAS;3	0.106	0.130	-0.024
FT. LEWIS 8C25	0.077	0.130	-0.053
BACK	0.103	0.130	-0.027
	0.105	0.130	-0.025
M=.734, Y'=0.01	0.252	0.270	-0.018
	0.301	0.270	0.031
	0.343	0.270	0.073
	0.287	0.270	0.017
	0.031	0.270	-0.239
	0.042	0.270	-0.228
	0.065	0.070	-0.005
	0.078	0.070	0.008
		Mean =	-0.041
		Std Dev =	0.092



TEST	RATE	SIM RATE	BASE RATE
LOKLEAK.SAS;2	0.025	0.040	-0.015
FT. LEWIS 4194	-0.006	0.040	-0.046
	0.021	0.040	-0.019
m=0.749, y'=0.013	-0.003	0.040	-0.043
	0.035	0.040	-0.005
	0.015	0.040	-0.025
	0.023	0.040	-0.017
	0.190	0.230	-0.040
	0.213	0.230	-0.017
	0.176	0.230	-0.054
	0.174	0.230	-0.056
	0.125	0.230	-0.105
	0.140	0.230	-0.090
	0.128	0.230	-0.102
	0.280	0.370	-0.090
	0.271	0.370	-0.099
	0.290	0.370	-0.080
	0.229	0.370	-0.141
	0.289	0.370	-0.081
	0.228	0.370	-0.142
	0.248	0.370	-0.122
		Mean =	-0.066
		Std Dev =	0.042



TEST	RATE	SIM RATE	BASE RATE
LLKRLS2.SAS;1	-0.094	0.080	-0.174
FT. LEWIS 10E10	-0.235	0.080	-0.315
	-0.124	0.080	-0.204
m=0.835, y'=-0.26	-0.089	0.080	-0.169
	-0.129	0.080	-0.209
	-0.104	0.080	-0.184
	-0.062	0.080	-0.142
	-0.115	0.140	-0.255
	-0.029	0.140	-0.169
	-0.046	0.140	-0.186
	-0.382	0.000	-0.382
	-0.336	0.000	-0.336
	-0.380	0.000	-0.380
	-0.430	0.000	-0.430
	-0.070	0.280	-0.350
	-0.023	0.280	-0.303
	-0.086	0.280	-0.366
	-0.092	0.280	-0.372
	-0.127	0.280	-0.407
		Mean =	-0.281
		Std Dev =	0.094



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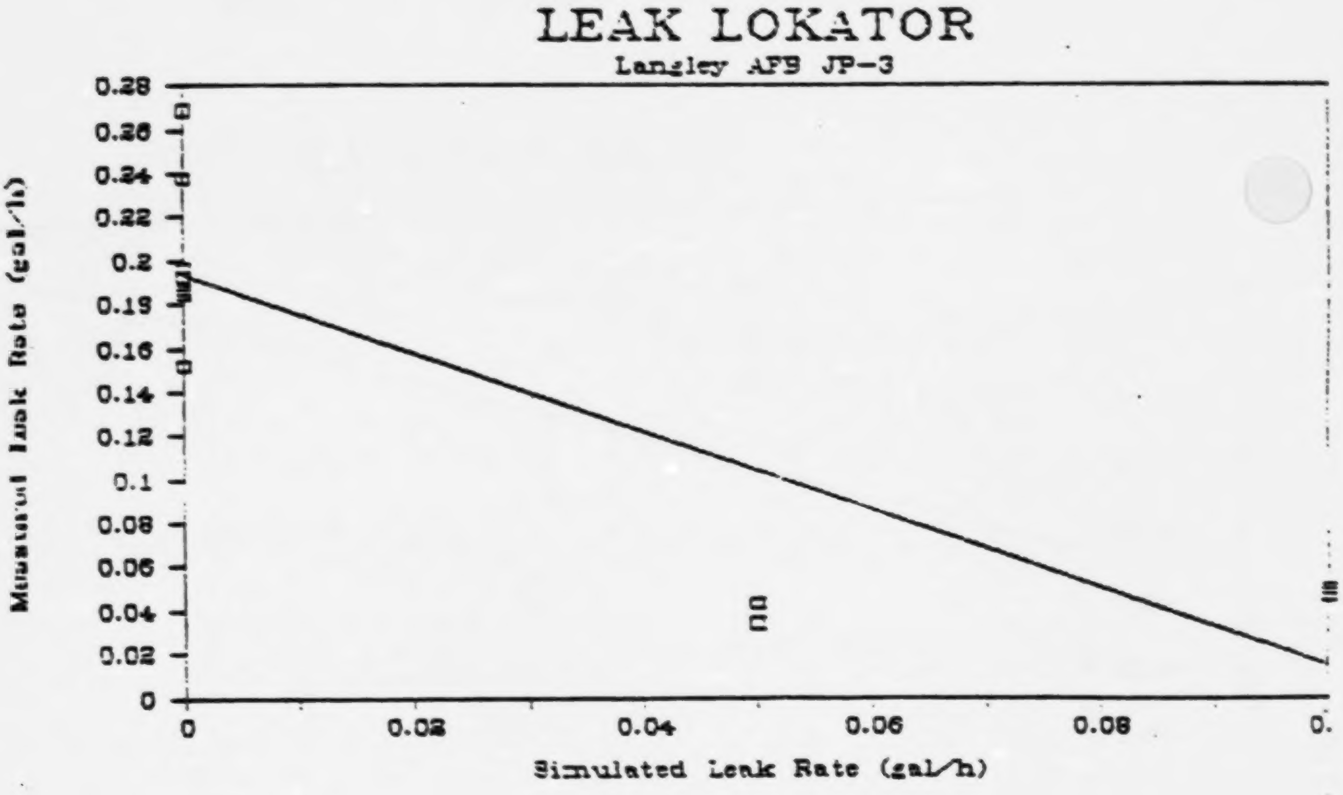
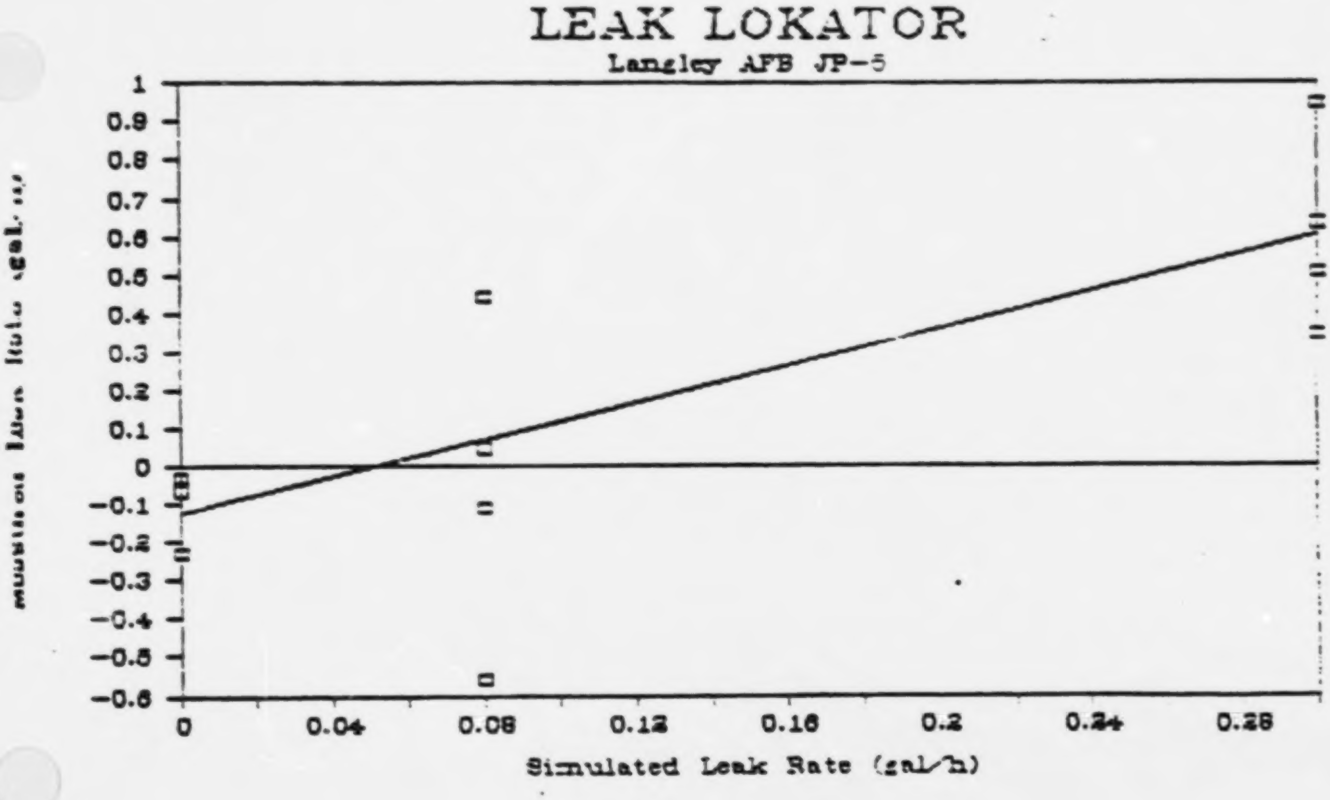
TEST                    RATE      SIM RATE   BASE RATE
-------------------------------------------------------
LLNGY1.SAS;1            0.034       0.050      -0.016
LANGLEY JP-3            0.043       0.050      -0.007
                        0.047       0.100      -0.053
m=-1.779, y'=0.19       0.050       0.100      -0.050
                        0.238       0.000       0.238
                        0.185       0.000       0.185
                        0.197       0.000       0.197
                        0.152       0.000       0.152
                        0.192       0.000       0.192
                        0.187       0.000       0.187
                        0.269       0.000       0.269
-------------------------------------------------------
                                 Mean =         0.118
                              Std Dev =         0.117
```



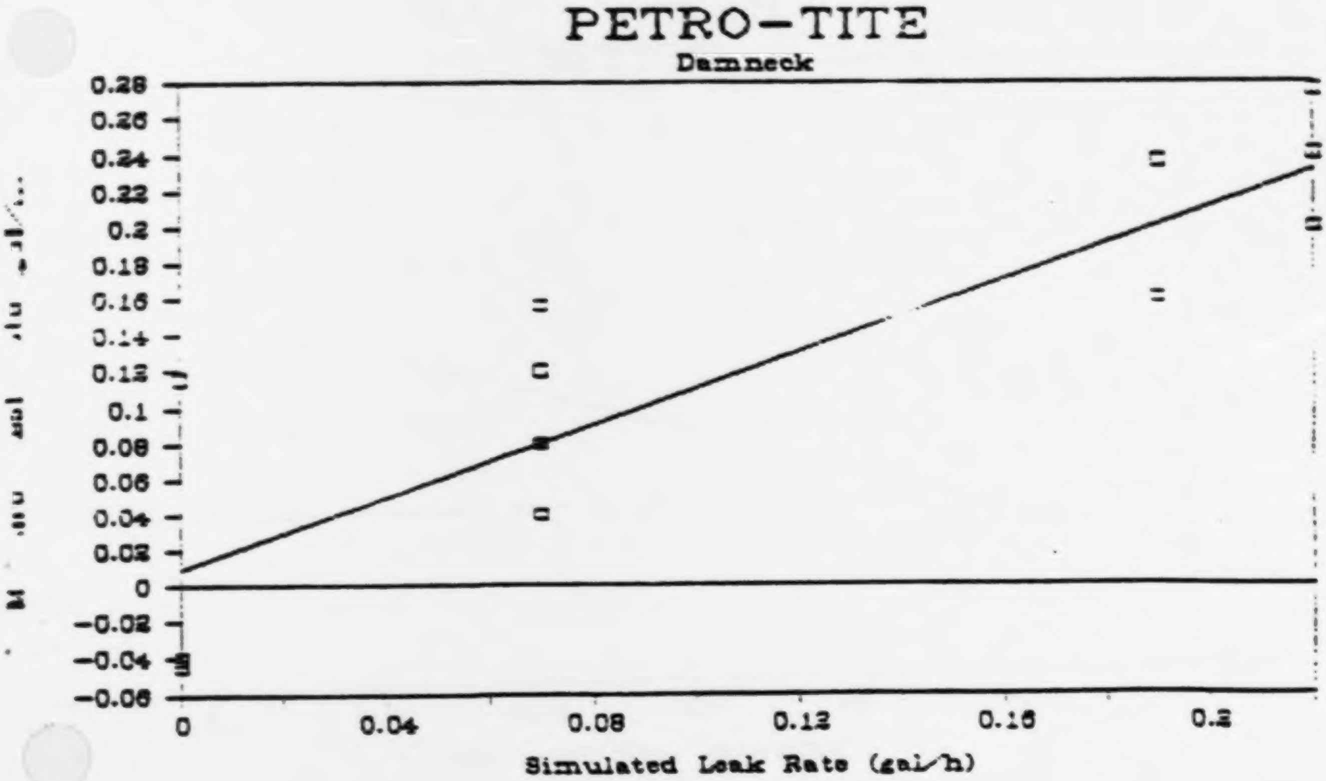
TEST	RATE	SIM RATE	BASE RATE
LLNGY2.SAS;1	0.443	0.080	0.363
LANGLEY JP-5	0.442	0.080	0.362
	-0.557	0.080	-0.637
m=2.429, y'=-0.12	-0.109	0.080	-0.189
	0.048	0.080	-0.032
	0.948	0.300	0.648
	0.345	0.300	0.045
	0.633	0.300	0.333
	0.504	0.300	0.204
	-0.029	0.000	-0.029
	-0.064	0.000	-0.064
	-0.231	0.000	-0.231
		Mean =	0.064
		Std Dev =	0.328



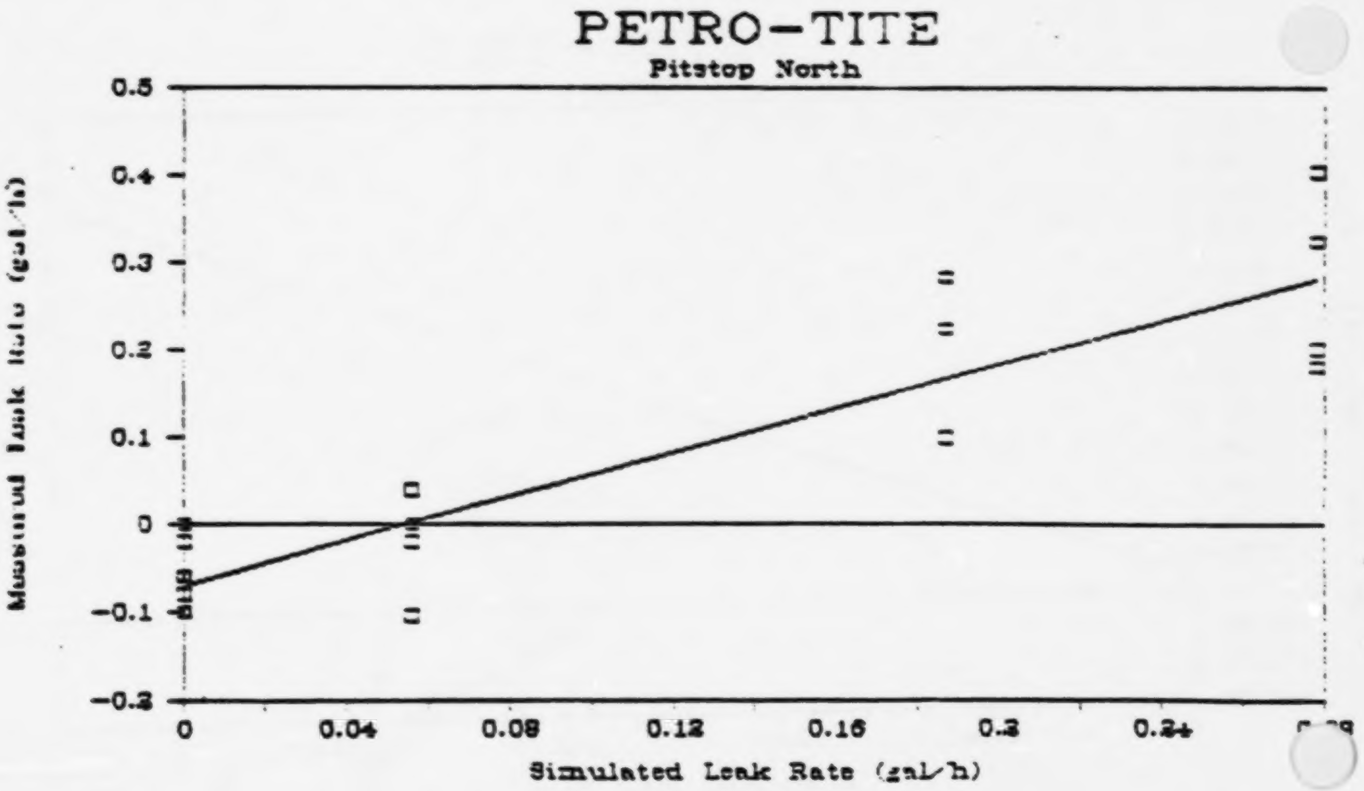
PETRO-TITE SIMULATION DATA

TEST	RATE	SIM RATE	BASE RATE
PETROTITE			
PETSCT.SAS;14	0.236	0.190	0.046
DAMNECK	0.160	0.190	-0.030
	0.236	0.190	0.046
m=1.01, y'=0.009	0.160	0.190	-0.030
	0.200	0.220	-0.020
	0.240	0.220	0.020
	0.276	0.220	0.056
	0.200	0.220	-0.020
	0.040	0.070	-0.030
	0.156	0.070	0.086
	0.080	0.070	0.010
	0.120	0.070	0.050
	-0.044	0.000	-0.044
	-0.044	0.000	-0.044
	0.116	0.000	0.116
	-0.040	0.000	-0.040

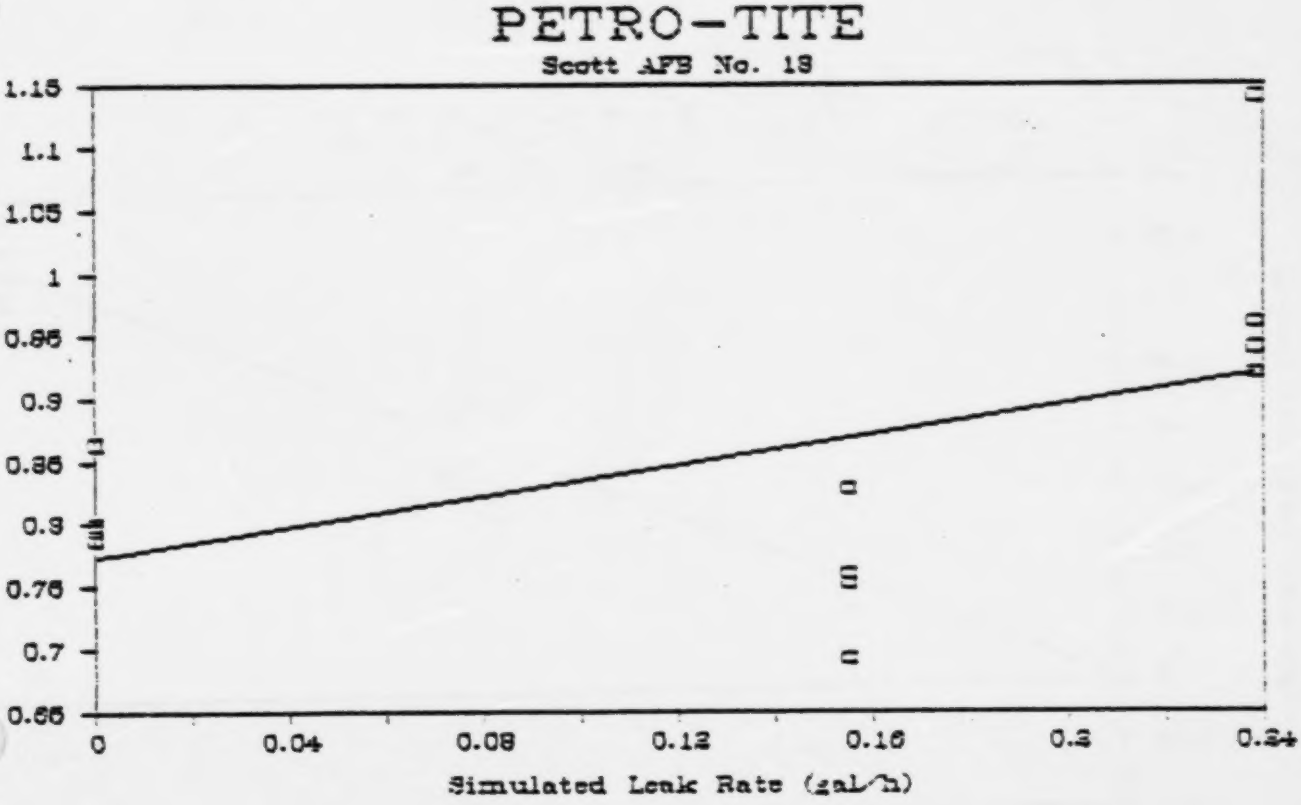
Mean = 0.011
Std Dev = 0.049



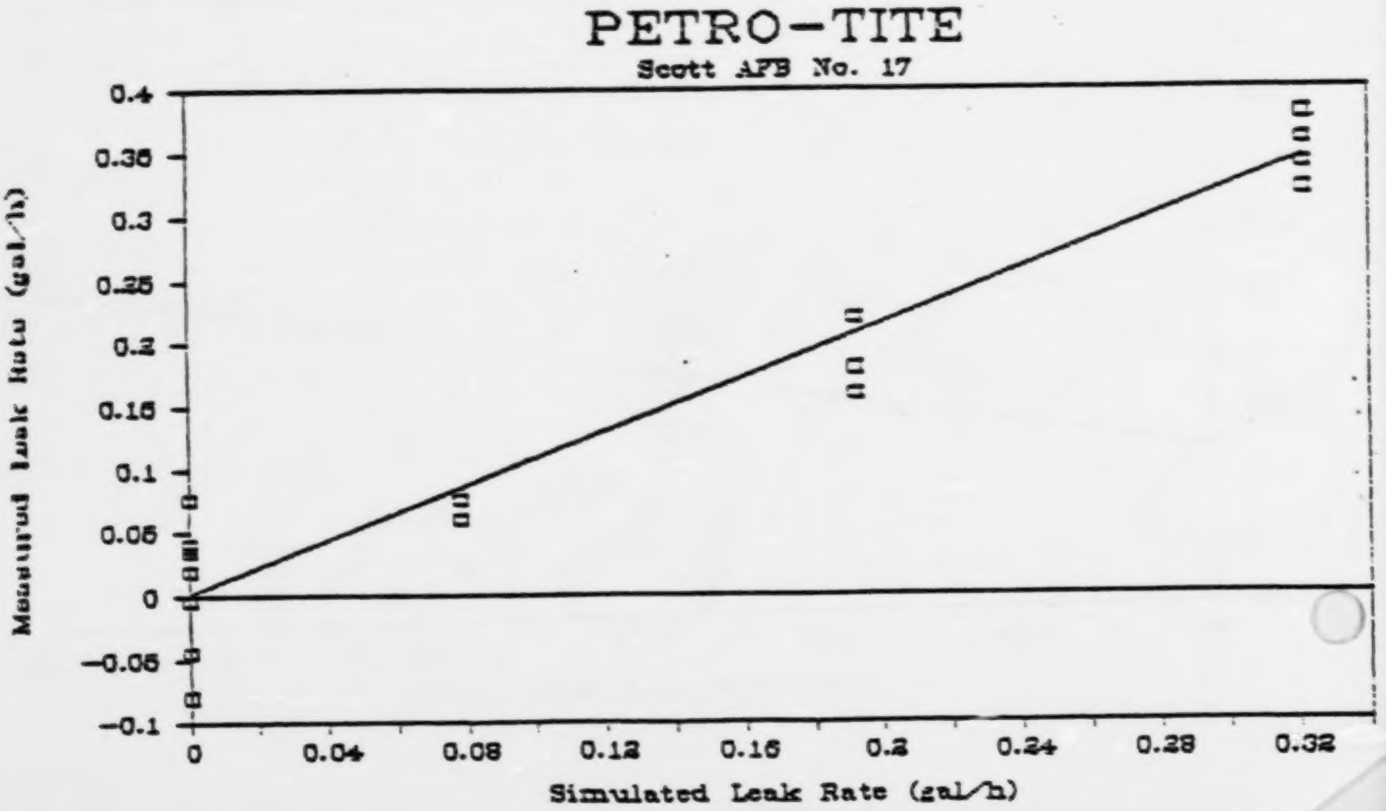
```
      TEST                     RATE      SIM RATE   BASE RATE
-------------------------------------------------------------
PETROPS.SAS;14               -0.100       0.000      -0.100
PITSTOP NORTH                -0.020       0.000      -0.020
                             -0.080       0.000      -0.080
m=1.26, y'=-0.069             0.000       0.000       0.000
                             -0.100       0.000      -0.100
                             -0.060       0.000      -0.060
                             -0.104       0.056      -0.160
                              0.000       0.056      -0.056
                              0.040       0.056      -0.016
                             -0.020       0.056      -0.076
                              0.284       0.187       0.097
                              0.100       0.187      -0.087
                              0.100       0.187      -0.087
                              0.224       0.187       0.037
                              0.405       0.278       0.127
                              0.324       0.278       0.046
                              0.180       0.278      -0.098
                              0.200       0.278      -0.078
-------------------------------------------------------------
                                         Mean =      -0.040
                                      Std Dev =       0.073
```



```
       TEST                 RATE      SIM RATE   BASE RATE
----------------------------------------------------------
PETSCT.SAS;15              0.800       0.000       0.800
SCOTT #18                  0.864       0.000       0.864
                           0.788       0.000       0.788
m=0.608, y'=0.774          0.796       0.000       0.796
                           1.140       0.238       0.902
                           0.940       0.238       0.702
                           0.960       0.238       0.722
                           0.920       0.238       0.682
                           0.760       0.155       0.605
                           0.828       0.155       0.673
                           0.752       0.155       0.597
                           0.692       0.155       0.537
----------------------------------------------------------
                                     Mean =        0.722
                                  Std Dev =        0.107
```



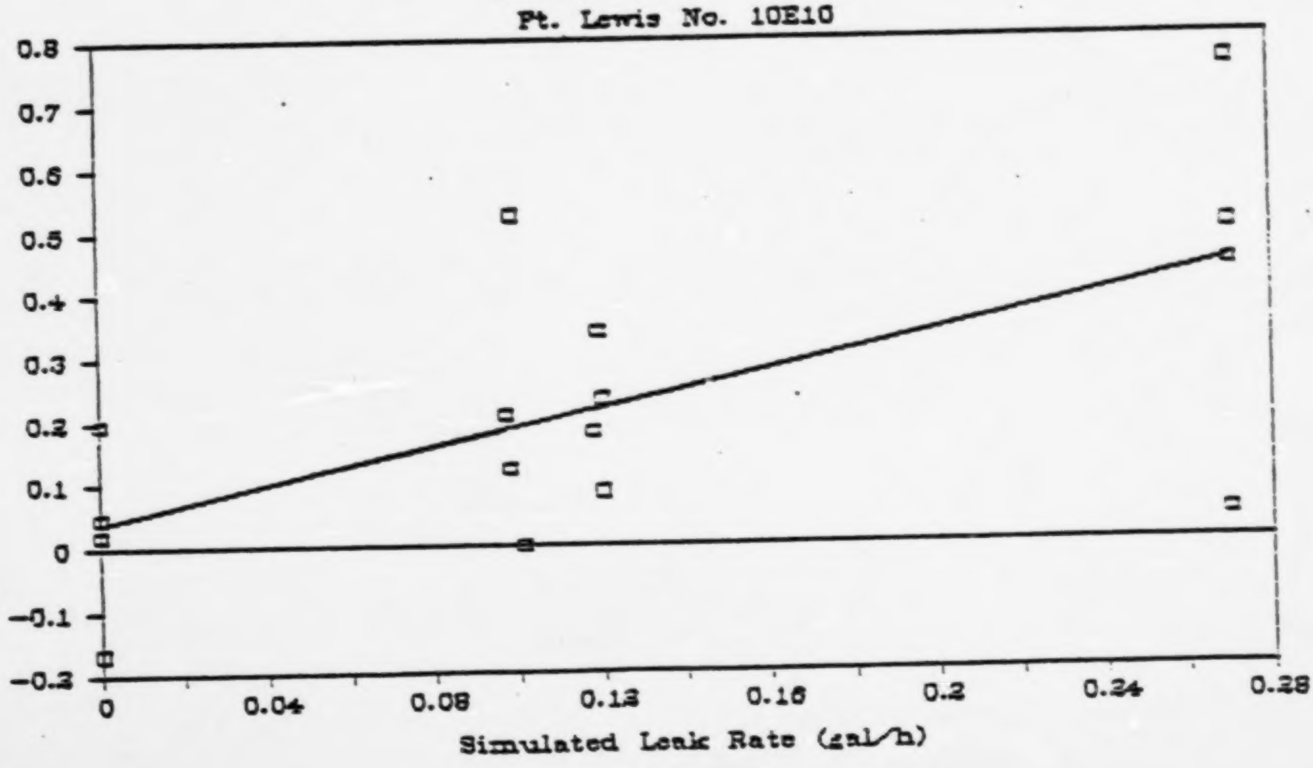
```
TEST                        RATE      SIM RATE   BASE RATE
-----------------------------------------------------------
PETSCT.SAS;16              -0.004      0.000      -0.004
SCOTT #17                  -0.044      0.000      -0.044
                           -0.004      0.000      -0.004
m=1.075, y'=-0.00           0.036      0.000       0.036
                            0.076      0.078      -0.002
                            0.076      0.078      -0.002
                            0.076      0.078      -0.002
                            0.060      0.078      -0.018
                            0.180      0.192      -0.012
                            0.160      0.192      -0.032
                            0.220      0.192       0.028
                            0.076      0.000       0.076
                           -0.080      0.000      -0.080
                            0.020      0.000       0.020
                            0.040      0.000       0.040
                            0.360      0.321       0.039
                            0.320      0.321      -0.001
                            0.340      0.321       0.019
                            0.380      0.321       0.059
                            0.360      0.321       0.039
-----------------------------------------------------------
                                  Mean =           0.008
                               Std Dev =           0.036
```



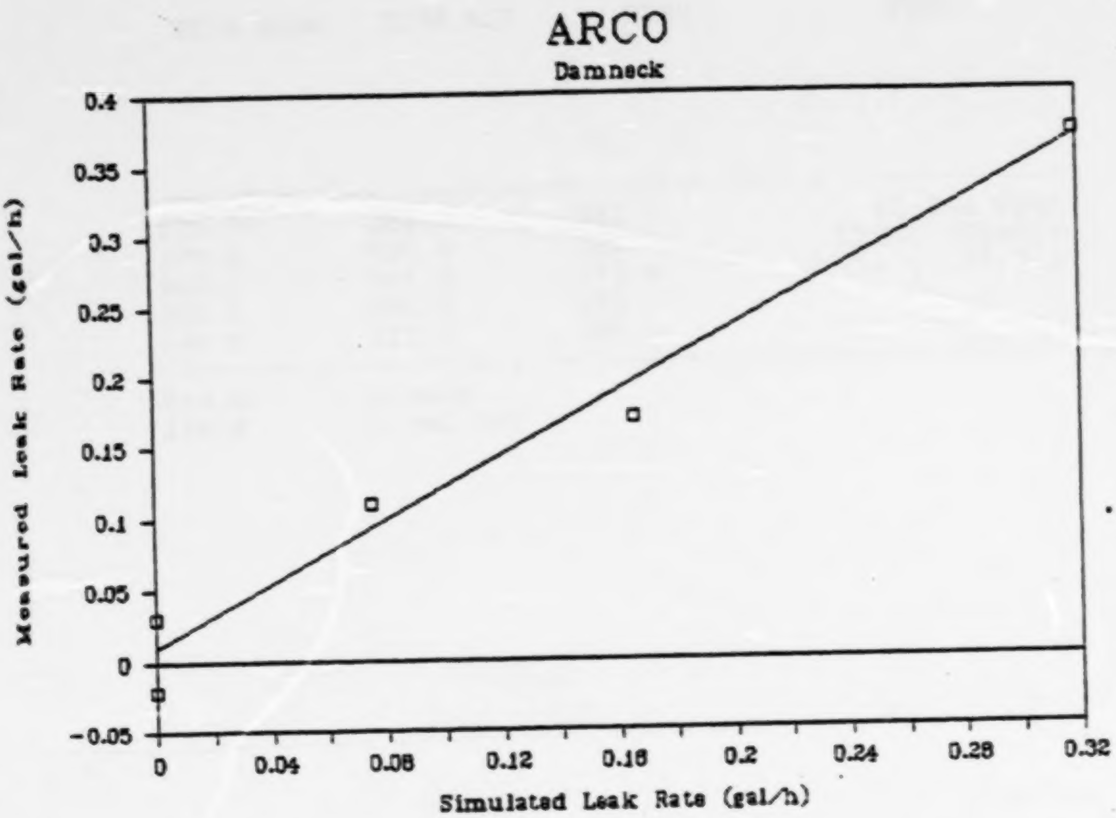
TEST	RATE	SIM RATE	BASE RATE
PETROLS.SAS;12	0.208	0.097	0.111
FT. LEWIS 10E10	0.020	0.000	0.020
	-0.168	0.000	-0.168
m=1.5, y'=0.038	0.196	0.000	0.196
	0.048	0.000	0.048
	0.120	0.098	0.022
	0.524	0.099	0.425
	0.000	0.101	-0.101
	0.044	0.270	-0.226
	0.500	0.270	0.230
	0.440	0.270	0.170
	0.760	0.270	0.490
	0.180	0.118	0.062
	0.084	0.120	-0.036
	0.232	0.120	0.112
	0.340	0.119	0.221
		Mean =	0.098
		Std Dev =	0.187

PETRO-TITE

Pt. Lewis No. 10E10

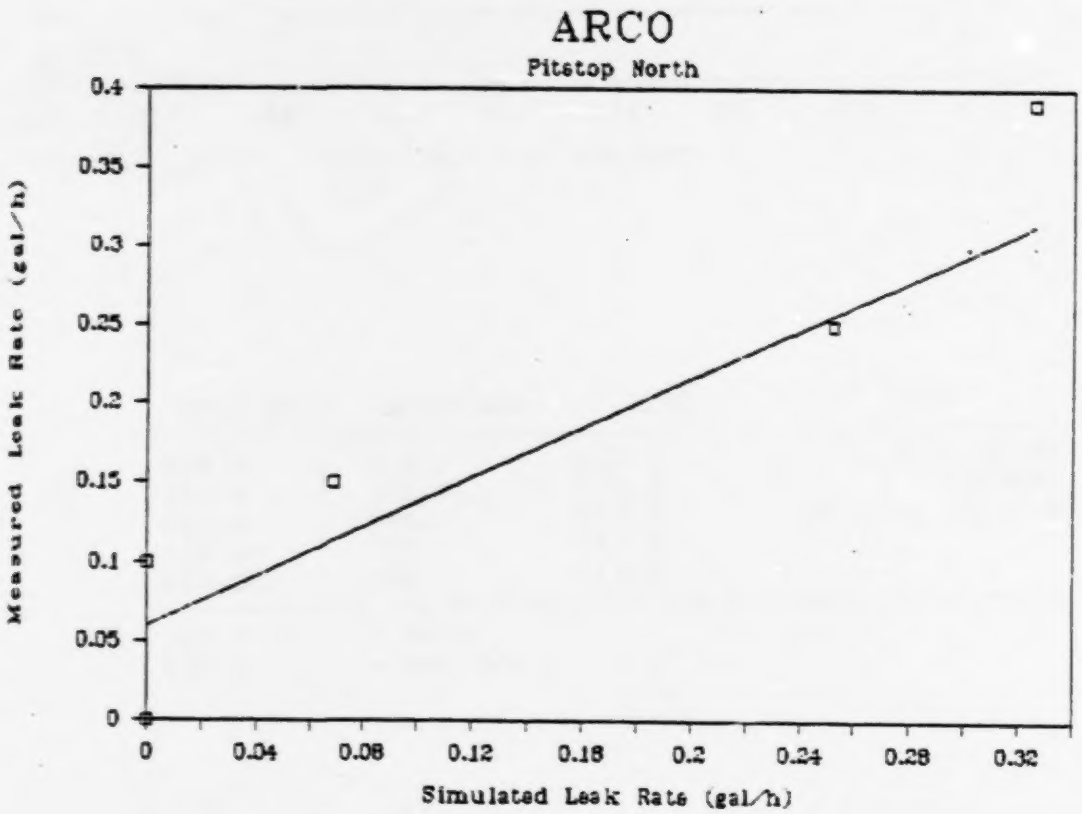


ARCO SIMULATION DATA

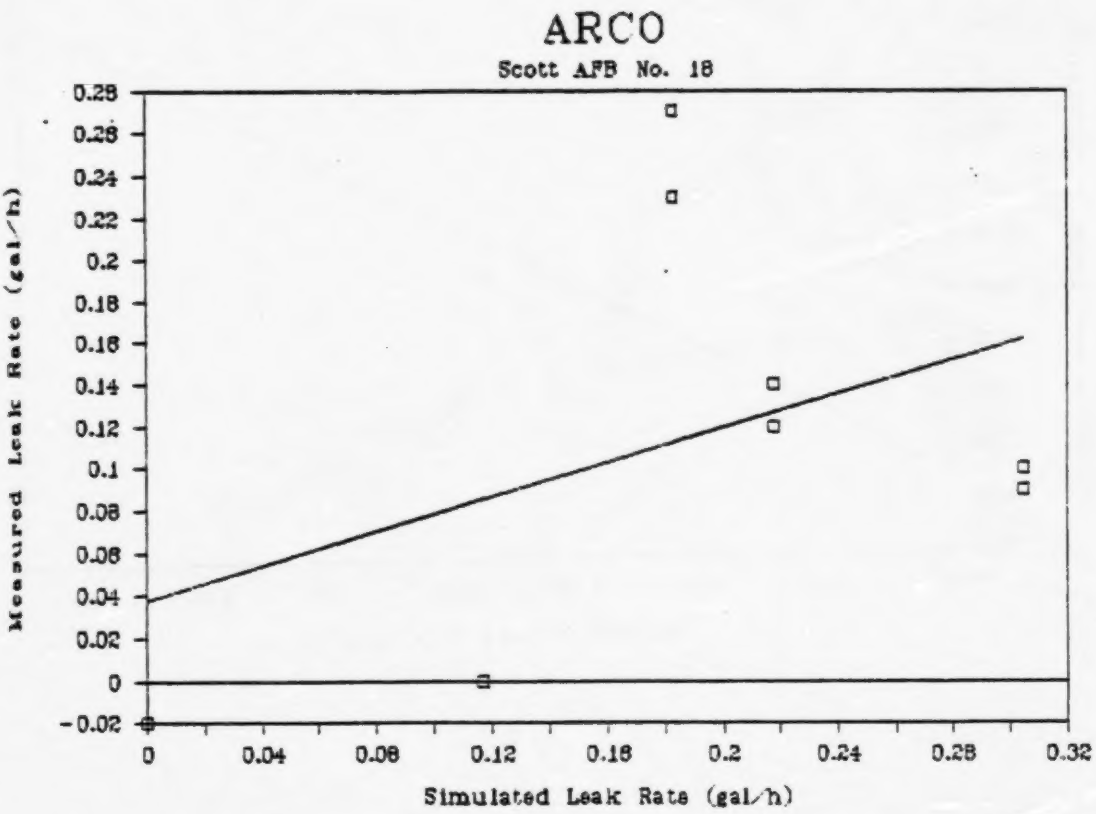


TEST	RATE	SIM RATE	BASE RATE
ARCODN.SAS;1	0.110	0.075	0.035
DAMNECK	0.370	0.319	0.051
m=1.12, y'=0.01	0.030	0.000	0.030
	-0.020	0.000	-0.020
	0.170	0.166	0.005
		Mean =	0.020
		Std Dev =	0.025

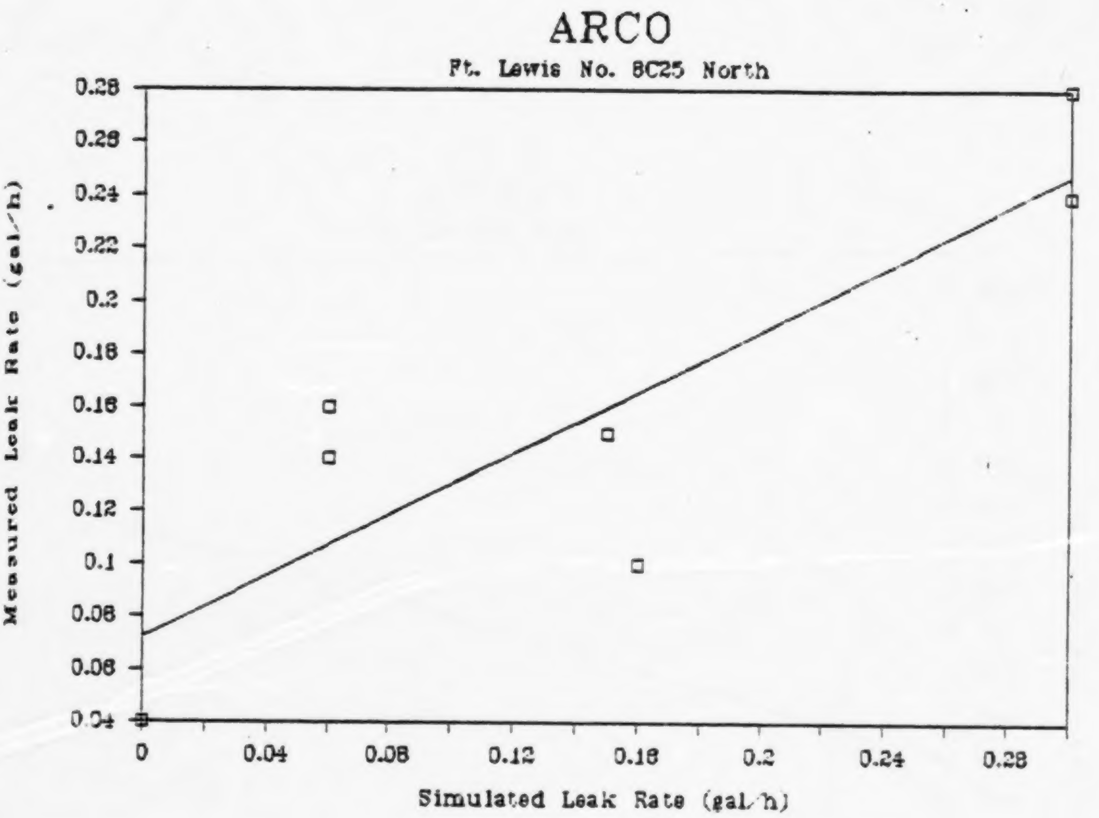
TEST	RATE	SIM RATE	BASE RATE
ARCO.SAS;10	0.250	0.252	-0.002
PITSTOP NORTH	0.150	0.069	0.081
m=0.78, y'=0.06	0.100	0.000	0.100
	0.000	0.000	0.000
	0.390	0.326	0.064
		Mean =	0.049
		Std Dev =	0.042



```
     TEST              RATE        SIM RATE   BASE RATE
-------------------------------------------------------
ARCOSCT.SAS;11         0.140        0.218       -0.078
SCOTT #18              0.120        0.218       -0.098
m=-0.408, y'=.038      0.230        0.183        0.047
                       0.270        0.183        0.087
                       0.090        0.305       -0.215
                       0.100        0.305       -0.205
                      -0.020        0.000       -0.020
                       0.000        0.117       -0.117
-------------------------------------------------------
                                  Mean =        -0.075
                               Std Dev =         0.102
```



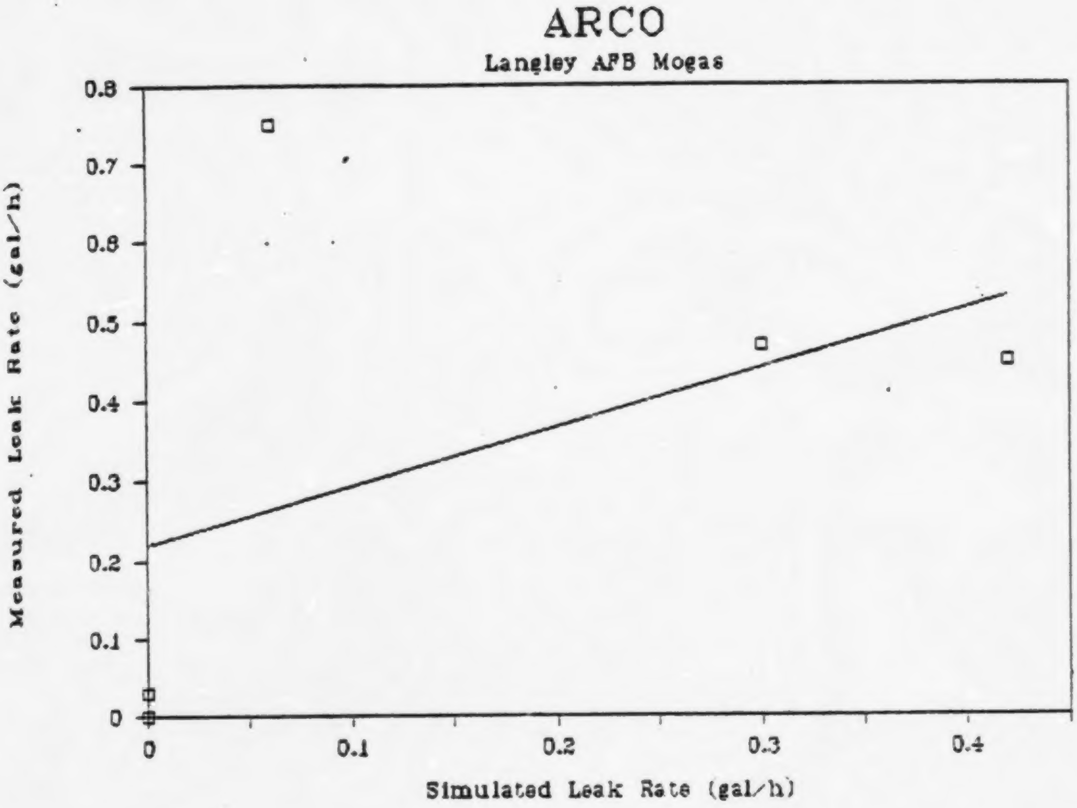
TEST	RATE	SIM RATE	BASE RATE
ARCO.SAS;7	0.150	0.150	0.000
FT. LEWIS 8C25	0.280	0.300	-0.020
NORTH	0.240	0.300	-0.060
m=0.587, y'=0.072	0.160	0.060	0.100
	0.040	0.000	0.040
	0.140	0.060	0.080
	0.100	0.160	-0.060
		Mean =	0.011
		Std Dev =	0.059


ARCO

Ft. Lewis No. 8C25 North

TEST	RATE	SIM RATE	BASE RATE
ARCOLNGY.SAS;1	0.470	0.300	0.170
LANGLEY MOGAS	0.450	0.420	0.030
m=0.74, y'=0.22	0.750	0.060	0.690
	0.030	0.000	0.030
	0.000	0.000	0.000

Mean = 0.184
Std Dev = 0.260



APPENDIX I

PILOT STUDY DATA

SITE DATA SUMMARY

Survey ID No. L290000528

Test Date Mar 13, 1985

Tank No. 1 of 2

Product Unleaded

Tank Size 1036 Gal.

TEST RESULTS

	System	Line 1	Line 2	Line 3	Line 4
Certified	Yes	N/A			
Rate	-0.01				
S.E.	0.0098				

Notes:

The standard error reported has been adjusted to a two-hour test period for consistency with future tests on the national survey. A negative sign indicates product loss (leak out).

01-Apr-85 Page 1

```
  LR  :Site Code L290000528 Fuel Type UNLEADED   Date        MAR.13,85
sig?  :Test Firm O.H.M.      Tank Vol        1036 T digits        11622
 N  Y  Test Crew BS,DP,JS    API Dens        60.1 T digits/F        317
    *  MRI Crew  BC,MG       Exp Coef  0.00061431 Leak Rate       0.007
```

Time Hr	Time Min	Level (div)	V Before (gal)	V After (gal)	Fuel Temp (digits)	Tcorr dV (gal)	Leak Rate (gal/h)
11	15	12	N/A	N/A	11784	N/A	N/A
11	30	12	0.500	0.575	11813	0.017	0.067
11	45	12	0.575	0.64	11843	0.005	0.019
12	0	12	0.64	0.71	11873	0.010	0.039
12	15	12	0.71	0.76	11900	-0.004	-0.017
12	30	12	0.76	0.82	11929	0.004	0.015
12	45	12	0.82	0.875	11957	-0.003	-0.013
13	0	12	0.21	0.26	11982	.000	-0.001
13	15	12	0.26	0.315	12011	-0.003	-0.013
13	30	12	0.315	0.365	12034	0.004	0.015
13	45	12	0.365	0.41	12061	-0.009	-0.037
14	0	12	0.41	0.455	12085	-0.003	-0.013
14	15	12	0.455	0.505	12107	0.006	0.023
14	30	12	0.505	0.55	12129	0.003	0.011
14	45	12	0.55	0.585	12148	-0.005	-0.021
15	0	12	0.585	0.615	12166	-0.006	-0.025
15	15	12	0.615	0.65	12185	-0.003	-0.013

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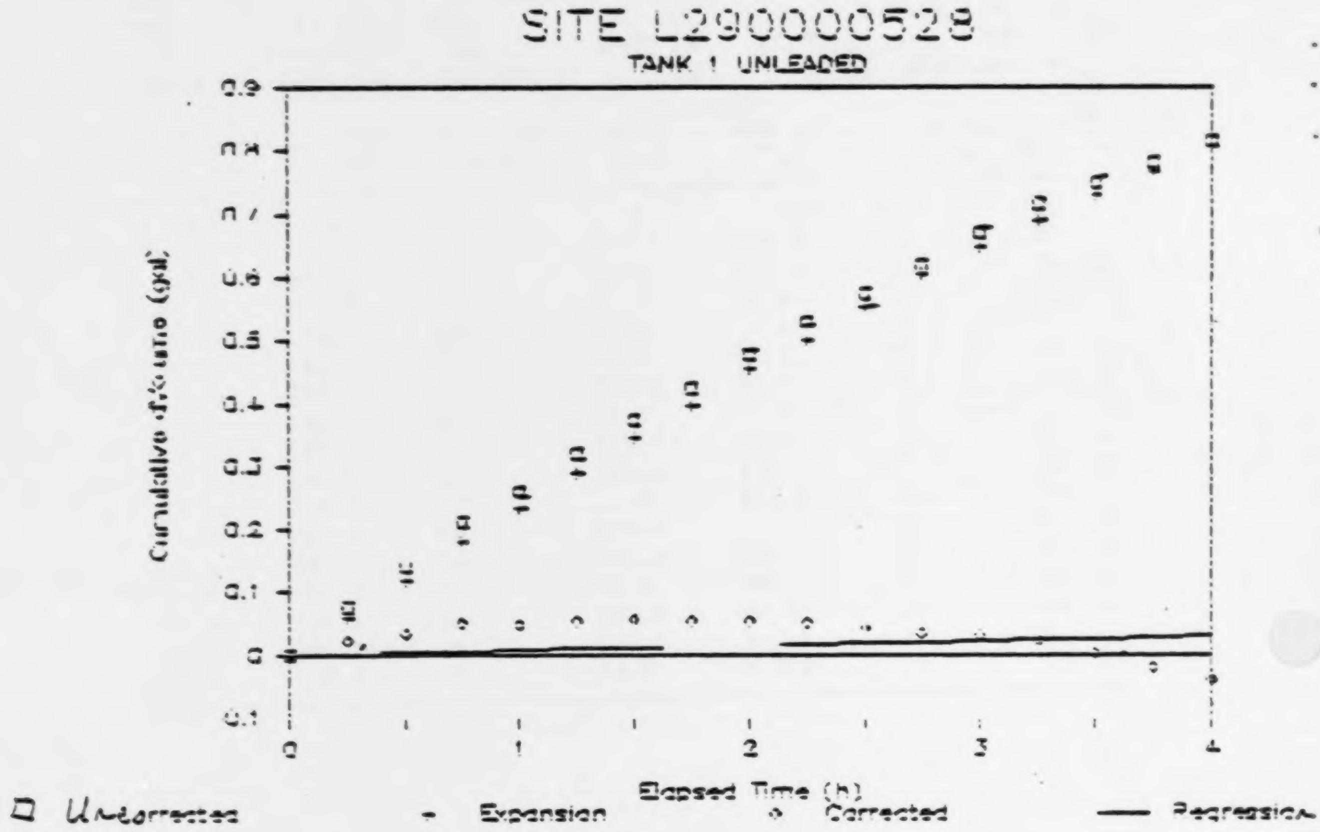
SITE L290000528
TANK 1 UNLEADED
Cumulative Volume (gal)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
1
2
3
4
Elapsed Time (h)
□ Uncorrected
+ Expansion
◇ Corrected
— Regression

SITE DATA SUMMARY

Survey ID No. L290000528

Tank No. 2 of 2

Tank Size 1036 Gal.

Test Date Mar 13, 1985

Product Leaded Regular

TEST RESULTS

	System	Line 1	Line 2	Line 3	Line 4
Certified	Yes	N/A			
Rate	-0.014				
S.E.	0.013				

Notes:

The standard error reported has been adjusted to a two-hour test period for consistency with future tests on the national survey. A negative sign indicates product loss (leak out).

```
 LR   !Site Code L290000529 Fuel Type REGULAR     Date       MAR.13,85
sig?  !Test Firm O.H.M.      Tank Vol        1036 T digits       10737
 N  Y  Test Crew BS,DP,JS    API Dens        63.4 T digits/F       311
 *     MRI Crew  BC,MG       Exp Coef 0.00063774 Leak Rate      -0.003

 Time    Level      V Before  V After   Fuel Temp  Tcorr dV Leak Rate
Hr  Min  (div)        (gal)     (gal)    (digits)    (gal)    (gal/h)
----------------------------------------------------------------------
13  30          12    N/A       N/A         10858    N/A        N/A
13  45          12     0.990     0.940      10879     0.005     0.022
14   0          12       0.5      0.65      10902     0.001     0.005
14  15          12      0.65     0.705      10926     0.004     0.016
14  30          12     0.705      0.74      10945    -0.005    -0.021
14  45          12      0.74     0.795      10968     0.006     0.025
15   0          12     0.795      0.83      10986    -0.003    -0.013
15  15          12      0.36     0.395      11005    -0.005    -0.021
15  30          12     0.395     0.435      11023     0.002     0.007
15  45          12     0.435     0.475      11041     0.002     0.007
16   0          12     0.475     0.505      11060    -0.010    -0.041
16  15          12     0.505      0.54      11079    -0.005    -0.021
16  30          12      0.54     0.575      11095     0.001     0.004
16  45          12     0.575     0.605      11112    -0.006    -0.024
17   0          12     0.605      0.63      11126    -0.005    -0.019
17  15          12      0.63      0.66      11143    -0.006    -0.024
17  30          12      0.66      0.69      11158    -0.002    -0.007
----------------------------------------------------------------------
```

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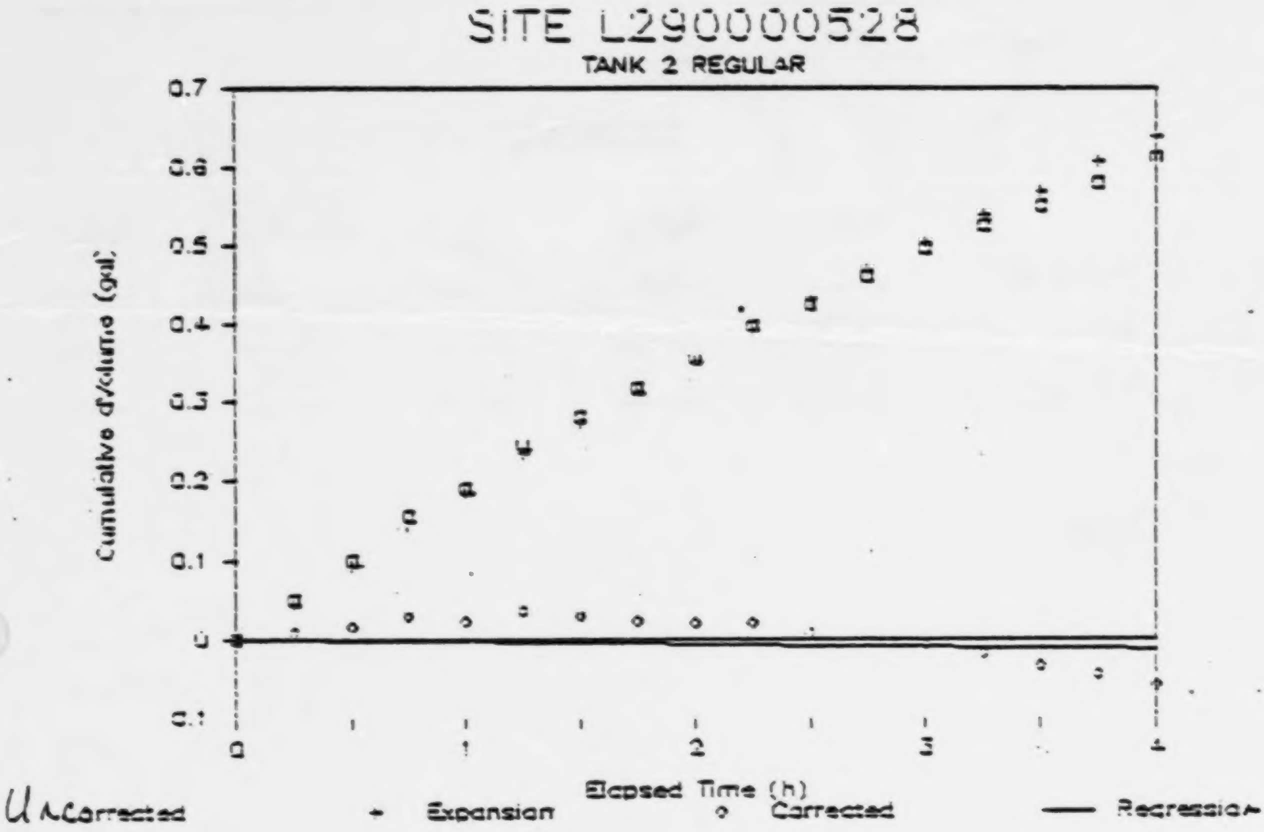


SITE DATA SUMMARY

Survey ID No. N290000006

Test Date Mar. 15, 1985

Tank No. 1 of 1

Product Unleaded

Tank Size 11907

TEST RESULTS

	System	Line 1	Line 2	Line 3	Line 4
Certified	Yes	N/A			
Rate	0.036				
S.E.	0.0074				

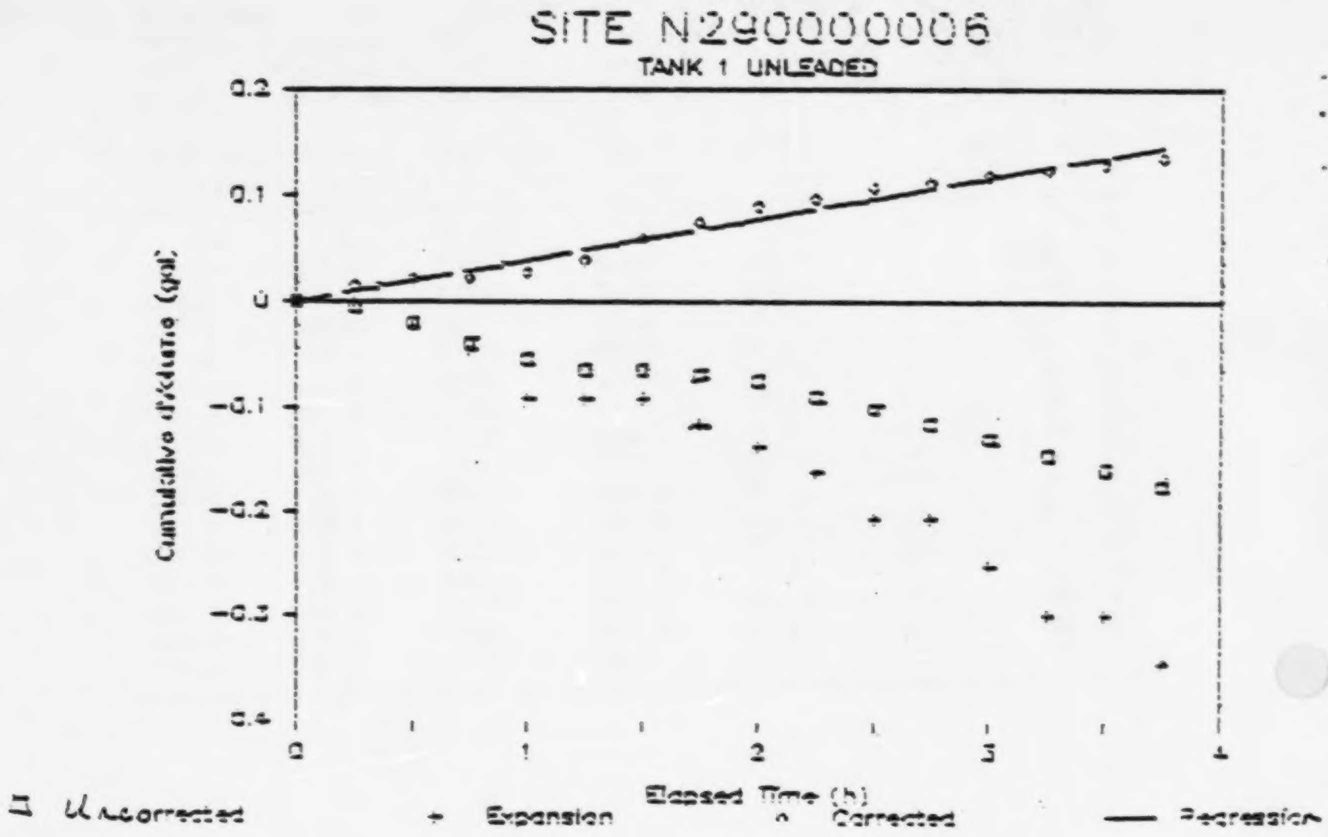
Notes:

Form 8429-001SDS

25-Mar-85 Page 1

LR	¦Site Code	N290000006	Fuel Type	UNLEADED	Date	MAR.15,85
sig?	¦Test Firm	O.H.M.	Tank Vol	11907	T digits	12297
N Y	Test Crew	BS,DP,JS	API Dens	60.7	T digits/F	320
*	MRI Crew	MG	Exp Coef	0.00061857	Leak Rate	0.039

Time Hr	Min	Level (div)	V Before (gal)	V After (gal)	Fuel Temp (digits)	Tcorr dV (gal)	Leak Rate (gal/h)
15	0	12	N/A	N/A	12297	N/A	N/A
15	15	12	0.080	0.075	12297	-0.005	-0.020
15	30	12	0.075	0.06	12296	0.008	0.032
15	45	12	0.06	0.04	12295	0.003	0.012
16	0	12	0.04	0.025	12293	0.031	0.124
16	15	12	0.025	0.015	12293	-0.010	-0.040
16	30	12	0.47	0.47	12293	0.000	0.000
16	45	12	0.47	0.465	12292	0.018	0.072
17	0	12	0.465	0.46	12291	0.018	0.072
17	15	12	0.46	0.445	12290	0.008	0.032
17	30	12	0.445	0.435	12288	0.036	0.144
17	45	12	0.435	0.42	12288	-0.015	-0.060
18	0	12	0.42	0.405	12286	0.031	0.124
18	15	12	0.405	0.39	12284	0.031	0.124
18	30	12	0.39	0.375	12284	-0.015	-0.060
18	45	12	0.375	0.36	12282	0.031	0.124


SITE N290000006
TANK 1 UNLEADED
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
Cumulative Volume (gal)
0
1
2
3
4
Elapsed Time (h)
Uncorrected
Expansion
Corrected
Regression

SITE DATA SUMMARY

Survey ID No. G290000123

Test Date Mar 16, 1985

Tank No. 1 of 1

Product Diesel

Tank Size 10383

TEST RESULTS

	System	Line 1	Line 2	Line 3	Line 4
Certified	No	No			
Rate	-0.056	-0.04			
S.E.	0.0067	0.005			

Notes:

The data report from OHM certifies this tank as tight. Their estimated leak rate is -0.029, within the NFPA standard. The system appears to have a slight leak, rate estimated as -0.056 gph. However, viewing the tank data only for the time that the line was isolated yields the conclusion that the tank is tight. For that time period, the estimated leak rate is -0.018 gph with an estimated standard error of 0.0094.

The conclusion we draw is that the tank is tight, but that there is a line leak, so that the system as a whole is not certifiable.

Form 8429-001SDS

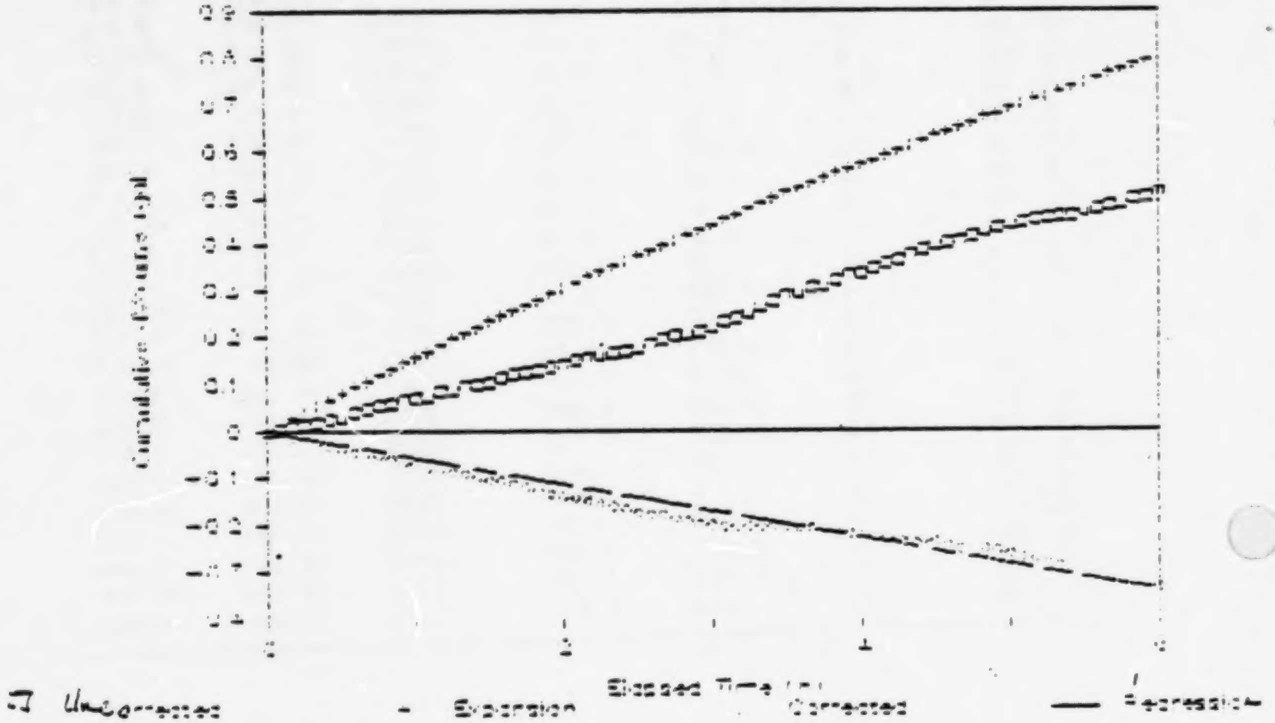
```
  LR  |Site Code 6290000123 Fuel Type DIESEL       Date      MAR.16,85
 sig? |Test Firm O.H.M.     Tank Vol          1036 T digits      10383
 N  Y  Test Crew 9S,DP,JS   API Dens          32.3 T digits/F      308
    *  MRI Crew  M.G.,K.W.  Exp Coef  0.00044635 Leak Rate    -0.057
```

Time Hr	 Min	Level (div)	V Before (gal)	V After (gal)	Fuel Temp (digits)	Tcorr dV (gal)	Leak Rate (gal/h)
11	0	12	N/A	N/A	10383	N/A	N/A
11	5	12	0.125	0.130	10392	-0.009	-0.102
11	10	12	0.13	0.135	10402	-0.010	-0.120
11	15	12	0.135	0.14	10410	-0.007	-0.084
11	20	12	0.14	0.145	10420	-0.010	-0.120
11	25	12	0.145	0.15	10428	-0.007	-0.084
11	30	12	0.15	0.155	10436	-0.007	-0.084
11	35	12	0.155	0.165	10446	-0.005	-0.060
11	40	12	0.165	0.175	10454	-0.002	-0.024
11	45	12	0.175	0.18	10463	-0.009	-0.102
11	50	12	0.18	0.185	10471	-0.007	-0.084
11	55	12	0.185	0.19	10480	-0.009	-0.102
12	0	12	0.19	0.195	10489	-0.009	-0.102
12	5	12	0.195	0.2	10496	-0.006	-0.066
12	10	12	0.2	0.21	10506	-0.005	-0.060
12	15	12	0.21	0.215	10516	-0.010	-0.120
12	20	12	0.215	0.22	10522	-0.004	-0.048
12	25	12	0.22	0.225	10530	-0.007	-0.084
12	30	12	0.225	0.23	10539	-0.009	-0.102
12	35	12	0.23	0.24	10547	-0.002	-0.024
12	40	12	0.24	0.245	10555	-0.007	-0.084
12	45	12	0.245	0.25	10562	-0.006	-0.066
12	50	12	0.25	0.255	10570	-0.007	-0.084
12	55	12	0.255	0.26	10579	-0.009	-0.102
13	0	12	0.26	0.255	10586	-0.006	-0.066
13	5	12	0.255	0.275	10593	-0.001	-0.006
13	10	12	0.275	0.28	10602	-0.009	-0.102
13	15	12	0.29	0.295	10610	-0.007	-0.084
13	20	12	0.295	0.29	10618	-0.007	-0.084
13	25	12	0.29	0.295	10625	-0.006	-0.066
13	30	12	0.295	0.3	10633	-0.007	-0.084
13	35	12	0.3	0.31	10639	0.001	0.012
13	40	12	0.31	0.32	10648	-0.004	-0.042
13	45	12	0.32	0.325	10655	-0.006	-0.066
13	50	12	0.325	0.33	10662	-0.006	-0.066
13	55	12	0.33	0.335	10669	-0.006	-0.056
14	0	12	0.335	0.345	10677	-0.002	-0.024
14	5	12	0.345	0.355	10686	-0.004	-0.042
14	10	12	0.355	0.365	10691	0.002	0.030
14	15	12	0.365	0.375	10700	-0.004	-0.042
14	20	12	0.375	0.39	10709	0.001	0.018
14	25	12	0.39	0.4	10715	0.001	0.012
14	30	12	0.4	0.41	10724	-0.004	-0.042
14	35	12	0.41	0.42	10731	-0.001	-0.006
14	40	12	0.42	0.43	10739	-0.001	-0.006
14	45	12	0.43	0.435	10744	-0.004	-0.048
14	50	12	0.435	0.445	10751	-0.001	-0.006
14	55	12	0.445	0.455	10757	0.001	0.012

15	0	12	0.455	0.46	10763	-0.004	-0.048
15	5	12	0.46	0.47	10770	-0.001	-0.006
15	10	12	0.47	0.48	10777	-0.001	-0.006
15	15	12	0.48	0.49	10783	0.001	0.012
15	20	12	0.49	0.5	10791	-0.002	-0.024
15	25	12	0.5	0.51	10799	-0.002	-0.024
15	30	12	0.51	0.52	10805	0.001	0.012
15	35	12	0.52	0.525	10811	-0.004	-0.048
15	40	12	0.525	0.53	10818	-0.006	-0.066
15	45	12	0.53	0.54	10824	0.001	0.012
15	50	12	0.54	0.55	10832	-0.002	-0.024
15	55	12	0.55	0.56	10836	0.004	0.048
16	0	12	0.56	0.565	10844	-0.007	-0.084
16	5	12	0.565	0.57	10850	-0.004	-0.048
16	10	12	0.57	0.575	10856	-0.004	-0.048
16	15	12	0.575	0.58	10860	-0.001	-0.012
16	20	12	0.58	0.585	10867	-0.006	-0.066
16	25	12	0.585	0.585	10874	-0.011	-0.126
16	30	12	0.585	0.595	10880	0.001	0.012
16	35	12	0.595	0.6	10886	-0.004	-0.048
16	40	12	0.6	0.605	10893	-0.006	-0.066
16	45	12	0.605	0.61	10899	-0.004	-0.048
16	50	12	0.525	0.535	10906	-0.001	-0.006
16	55	12	0.535	0.54	10912	-0.004	-0.048
17	0	12	0.54	0.545	10918	-0.004	-0.048

SITE G290000123

TANK 1 DIESEL



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SITE DATA SUMMARY

Survey ID No. N290000010

Test Date Mar 18, 1985

Tank No. 1 of 3

Product Regular

Tank Size 6006

TEST RESULTS

	System	Line 1	Line 2	Line 3	Line 4
Certified	Yes	NO	No	No	Yes
Rate	0.036	BCV	-0.031	BCV	-0.01
S.E.	0.024	NA	---	---	---

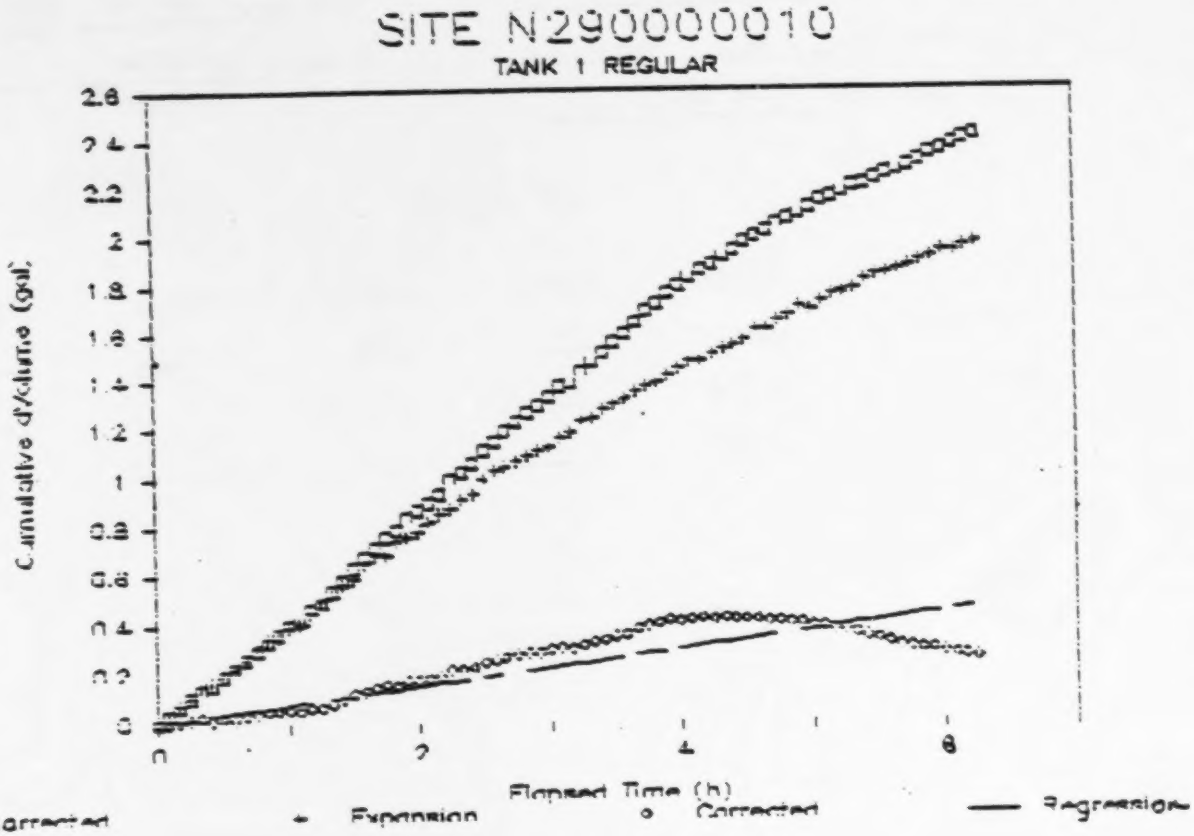
Notes:

Two of the lines could not be certified because they had bad check valves (BCV). One line had a noticible lead (-0.031 gph), and the other had an estimated leak below the line threshold of -0.025 gph.

```
 LR  !Site Code N290000010 Fuel Type REGULAR     Date       MAR.18.85
sig? !Test Firm OHM        Tank Vol        6006 T digits         11966
N  Y  Test Crew RS,DP,JS   API Dens        61.8 T digits/F         318
   *  MRI Crew  SR,WB      Exp Coef 0.00062538 Leak Rate         0.074
```

Time Hr	Min	Level (div)	V Before (gal)	V After (gal)	Fuel Temp (digits)	Tcorr dV (gal)	Leak Rate (gal/h)
12	30	12	N/A	N/A	12066	N/A	N/A
12	35	12	0.345	0.375	12068	0.006	0.076
12	40	12	0.375	0.415	12072	-0.007	-0.088
12	45	12	0.415	0.45	12075	.000	-0.006
12	50	12	0.45	0.48	12079	-0.017	-0.208
12	55	12	0.48	0.5	12081	-0.004	-0.044
13	0	12	0.5	0.54	12083	0.016	0.196
13	5	12	0.54	0.565	12085	0.001	0.016
13	10	12	0.565	0.605	12088	0.005	0.054
13	15	12	0.605	0.64	12092	-0.012	-0.148
13	20	12	0.64	0.675	12095	.000	-0.006
13	25	12	0.345	0.375	12096	0.018	0.219
13	30	12	0.375	0.41	12099	.000	-0.006
13	35	12	0.41	0.435	12100	0.013	0.158
13	40	12	0.435	0.475	12104	-0.007	-0.088
13	45	12	0.475	0.505	12108	-0.017	-0.208
13	50	12	0.505	0.55	12111	0.010	0.114
13	55	12	0.55	0.6	12114	0.015	0.174
14	0	12	0.6	0.65	12116	0.025	0.316
14	5	12	0.65	0.69	12120	-0.007	-0.088
14	10	12	0.69	0.73	12124	-0.007	-0.088
14	15	12	0.73	0.775	12124	0.045	0.540
14	20	12	0.295	0.32	12129	-0.034	-0.418
14	25	12	0.32	0.37	12130	0.038	0.458
14	30	12	0.37	0.4	12132	0.006	0.076
14	35	12	0.4	0.43	12135	-0.005	-0.066
14	40	12	0.43	0.47	12138	0.005	0.054
14	45	12	0.47	0.525	12140	0.031	0.376
14	50	12	0.525	0.555	12143	-0.005	-0.066
14	55	12	0.555	0.595	12145	0.016	0.196
15	0	12	0.595	0.64	12150	-0.014	-0.170
15	5	12	0.64	0.68	12153	0.005	0.054
15	10	12	0.68	0.725	12154	0.033	0.398
15	15	12	0.725	0.76	12156	0.011	0.136
15	20	12	0.76	0.795	12158	0.011	0.136
15	25	12	0.29	0.31	12160	0.006	0.076
15	30	12	0.31	0.35	12161	0.029	0.338
15	35	12	0.35	0.39	12164	0.005	0.054
15	40	12	0.39	0.41	12166	-0.004	-0.044
15	45	12	0.41	0.455	12170	-0.002	-0.029
15	50	12	0.455	0.495	12171	0.028	0.338
15	55	12	0.495	0.535	12174	0.005	0.054
15	0	12	0.535	0.575	12176	0.016	0.196
16	5	12	0.575	0.615	12178	0.016	0.196
16	10	12	0.615	0.66	12180	0.021	0.256
16	15	12	0.66	0.705	12182	0.021	0.256
16	20	12	0.705	0.74	12183	0.023	0.278
16	25	12	0.74	0.785	12186	0.010	0.114

16	30	12	0.785	0.81	12188	0.001	0.016
16	35	12	0.81	0.845	12191	.000	-0.006
16	40	12	0.845	0.88	12191	0.035	0.420
16	45	12	0.88	0.9	12193	-0.004	-0.044
16	50	12	0.24	0.275	12195	0.011	0.136
16	55	12	0.275	0.3	12196	0.013	0.158
17	0	12	0.3	0.33	12198	0.006	0.075
17	5	12	0.33	0.355	12202	-0.022	-0.258
17	10	12	0.355	0.38	12202	0.025	0.300
17	15	12	0.38	0.41	12205	-0.005	-0.066
17	20	12	0.41	0.43	12207	-0.004	-0.044
17	25	12	0.43	0.455	12210	-0.010	-0.125
17	30	12	0.455	0.475	12209	0.032	0.382
17	35	12	0.475	0.5	12212	-0.010	-0.125
17	40	12	0.5	0.515	12214	-0.009	-0.104
17	45	12	0.515	0.54	12215	0.013	0.158
17	50	12	0.54	0.56	12216	0.008	0.098
17	55	12	0.56	0.57	12219	-0.025	-0.306
18	0	12	0.57	0.59	12221	-0.004	-0.044
18	5	12	0.59	0.61	12222	0.008	0.098
18	10	12	0.61	0.625	12223	0.003	0.038
18	15	12	0.625	0.64	12224	0.003	0.038
18	20	12	0.64	0.665	12225	0.001	0.016
18	25	12	0.665	0.69	12227	0.013	0.158
18	30	12	0.69	0.71	12230	-0.015	-0.186
18	35	12	0.71	0.73	12229	0.032	0.382
18	40	12	0.73	0.75	12231	-0.004	-0.044
18	45	12	0.75	0.77	12232	0.008	0.098


SITE N290000010
TANK 1 REGULAR
Cumulative d/Volume (gal)
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
Elapsed Time (h)
□ Uncorrected
+ Expansion
○ Corrected
— Regression

SITE DATA SUMMARY

Survey ID No. N290000010

Test Date Mar 18, 1985

Tank No. 3 of 3

Product Unleaded

Tank Size 6006 Gal.

TEST RESULTS

	System	Line 1	Line 2	Line 3	Line 4
Certified	Yes	No	Yes	--	
Rate	0.013	-0.032	-0.015	--	
S.E.	0.035	---	---		

Notes:

Form 8429-001SDS

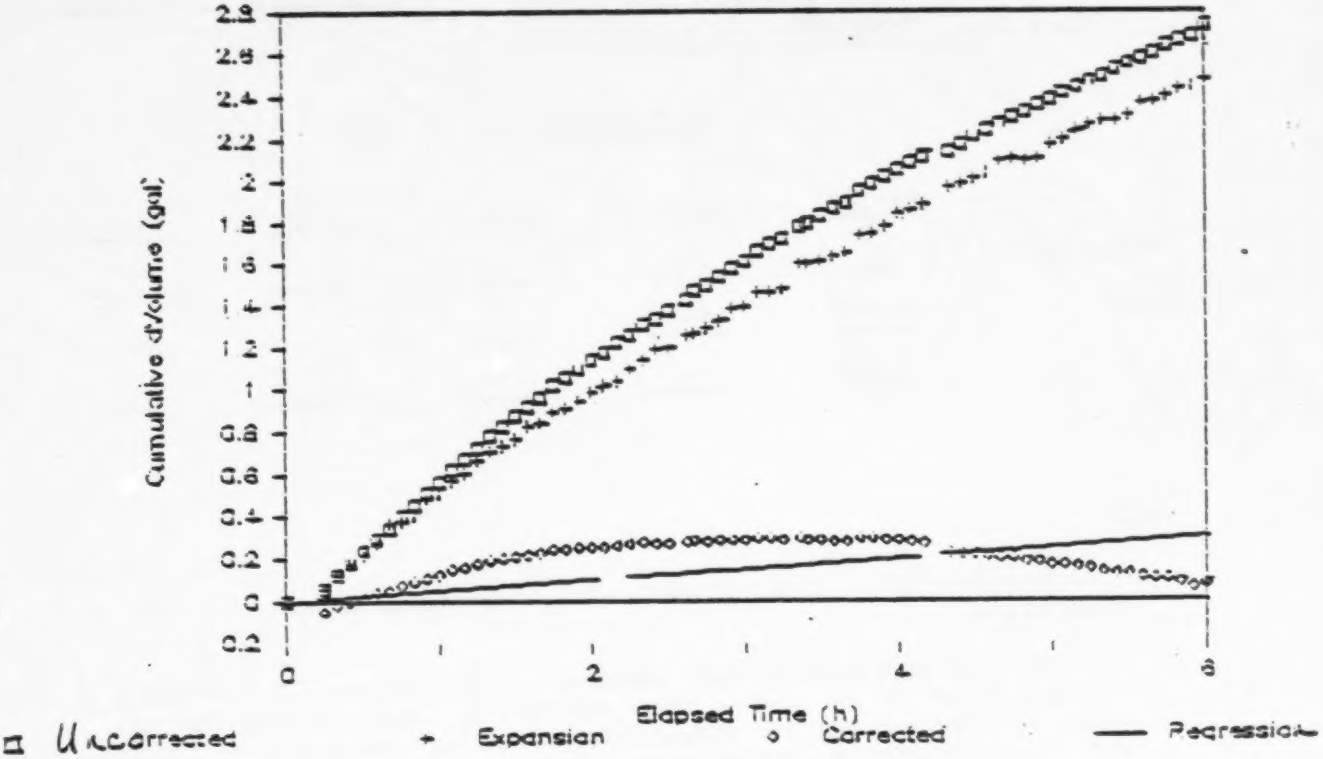
```
 LR  :Site Code N290000010 Fuel Type UNLEADED   Date        MAR 18 85
sig? :Test Firm OHM        Tank Vol         6006 T digits       12171
N  Y :Test Crew RS,DP,JS   API Dens         59.3 T digits/F       320
   *  MRI Crew  SR,WB      Exp Coef 0.00060863 Leak Rate        0.050
```

Time Hr	Time Min	Level (div)	V Before (gal)	V After (gal)	Fuel Temp (digits)	Tcorr dV (gal)	Leak Rate (gal/h)
13	45	12	N/A	N/A	12257	N/A	N/A
14	0	12	0.680	0.740	12252	0.003	0.012
14	5	12	0.155	0.22	12258	-0.004	-0.042
14	10	12	0.22	0.275	12272	0.009	0.112
14	15	12	0.275	0.33	12276	0.009	0.112
14	20	12	0.33	0.39	12281	0.003	0.035
14	25	12	0.39	0.44	12289	-0.041	-0.497
14	30	12	0.44	0.5	12290	0.049	0.583
14	35	12	0.5	0.55	12293	0.016	0.189
14	40	12	0.105	0.16	12300	-0.025	-0.300
14	45	12	0.16	0.215	12302	0.032	0.386
14	50	12	0.215	0.275	12307	0.003	0.035
14	55	12	0.275	0.32	12310	0.011	0.129
15	0	12	0.32	0.375	12315	-0.002	-0.025
15	5	12	0.375	0.43	12319	0.009	0.112
15	10	12	0.43	0.475	12321	0.022	0.256
15	15	12	0.475	0.525	12324	0.016	0.189
15	20	12	0.525	0.57	12329	-0.012	-0.145
15	25	12	0.165	0.21	12331	0.022	0.256
15	30	12	0.21	0.255	12335	0.009	0.112
15	35	12	0.255	0.295	12337	0.007	0.086
15	40	12	0.295	0.34	12340	0.011	0.129
15	45	12	0.34	0.38	12343	0.006	0.063
15	50	12	0.38	0.415	12346	0.001	0.009
15	55	12	0.415	0.465	12348	0.027	0.326
16	0	12	0.465	0.505	12353	-0.017	-0.205
16	5	12	0.505	0.55	12357	-0.001	-0.008
16	10	12	0.55	0.58	12361	-0.016	-0.188
16	15	12	0.58	0.62	12362	0.029	0.343
16	22	12	0.065	0.12	12367	-0.002	-0.018
16	25	12	0.12	0.155	12368	0.024	0.472
16	30	12	0.155	0.185	12370	0.007	0.086
16	35	12	0.185	0.23	12373	0.011	0.129
15	40	12	0.23	0.255	12378	-0.022	-0.255
15	45	12	0.255	0.3	12379	0.024	0.293
16	50	12	0.3	0.35	12385	-0.019	-0.222
16	55	12	0.35	0.385	12385	0.035	0.420
17	0	12	0.385	0.415	12386	0.019	0.223
17	7	12	0.415	0.47	12397	-0.071	-0.506
17	10	12	0.47	0.49	12397	0.020	0.400
17	15	12	0.49	0.52	12398	0.019	0.223
17	20	12	0.52	0.555	12400	0.012	0.146
17	25	12	0.2	0.23	12402	0.007	0.086
17	30	12	0.23	0.285	12409	-0.025	-0.300
17	35	12	0.285	0.32	12410	0.024	0.293
17	40	12	0.32	0.355	12413	0.001	0.009
17	45	12	0.355	0.39	12418	-0.022	-0.255
17	50	12	0.39	0.42	12420	0.007	0.086

17	55	12	0.42	0.445	12422	0.002	0.025
18	5	12	0.5	0.53	12429	-0.050	-0.300
18	10	12	0.53	0.56	12431	0.007	0.086
18	15	12	0.56	0.5	12433	0.017	0.206
18	20	12	0.6	0.63	12435	0.007	0.086
18	25	12	0.63	0.655	12440	-0.032	-0.385
18	30	12	0.36	0.395	12441	0.024	0.293
18	35	12	0.395	0.42	12440	0.036	0.437
18	40	12	0.42	0.45	12441	0.019	0.223
18	45	12	0.45	0.475	12447	-0.044	-0.522
18	50	12	0.475	0.51	12449	0.012	0.146
18	55	12	0.51	0.54	12453	-0.016	-0.188
19	0	12	0.54	0.565	12455	0.002	0.025
19	5	12	0.565	0.59	12457	0.002	0.025
19	10	12	0.59	0.62	12457	0.030	0.360
19	15	12	0.62	0.65	12459	0.007	0.086
19	20	12	0.65	0.675	12464	-0.032	-0.385
19	25	12	0.675	0.7	12465	0.014	0.153
19	30	12	0.245	0.28	12467	0.012	0.146
19	35	12	0.28	0.305	12470	-0.009	-0.111
19	40	12	0.305	0.315	12471	-0.001	-0.017
19	45	12	0.315	0.37	12474	0.021	0.249

SITE N2900000T0

TANK 3 UNLEADED



SITE DATA SUMMARY

Survey ID No. N310000109　　Test Date Mar 20, 1985

Tank No. 1 of 1　　Product Unleaded

Tank Size 8000 Gal.

TEST RESULTS

	System	Line 1	Line 2	Line 3	Line 4
Certified	Yes	No	--		
Rate	0.0078	BCV			
S.E.	0.014	---			

Notes:

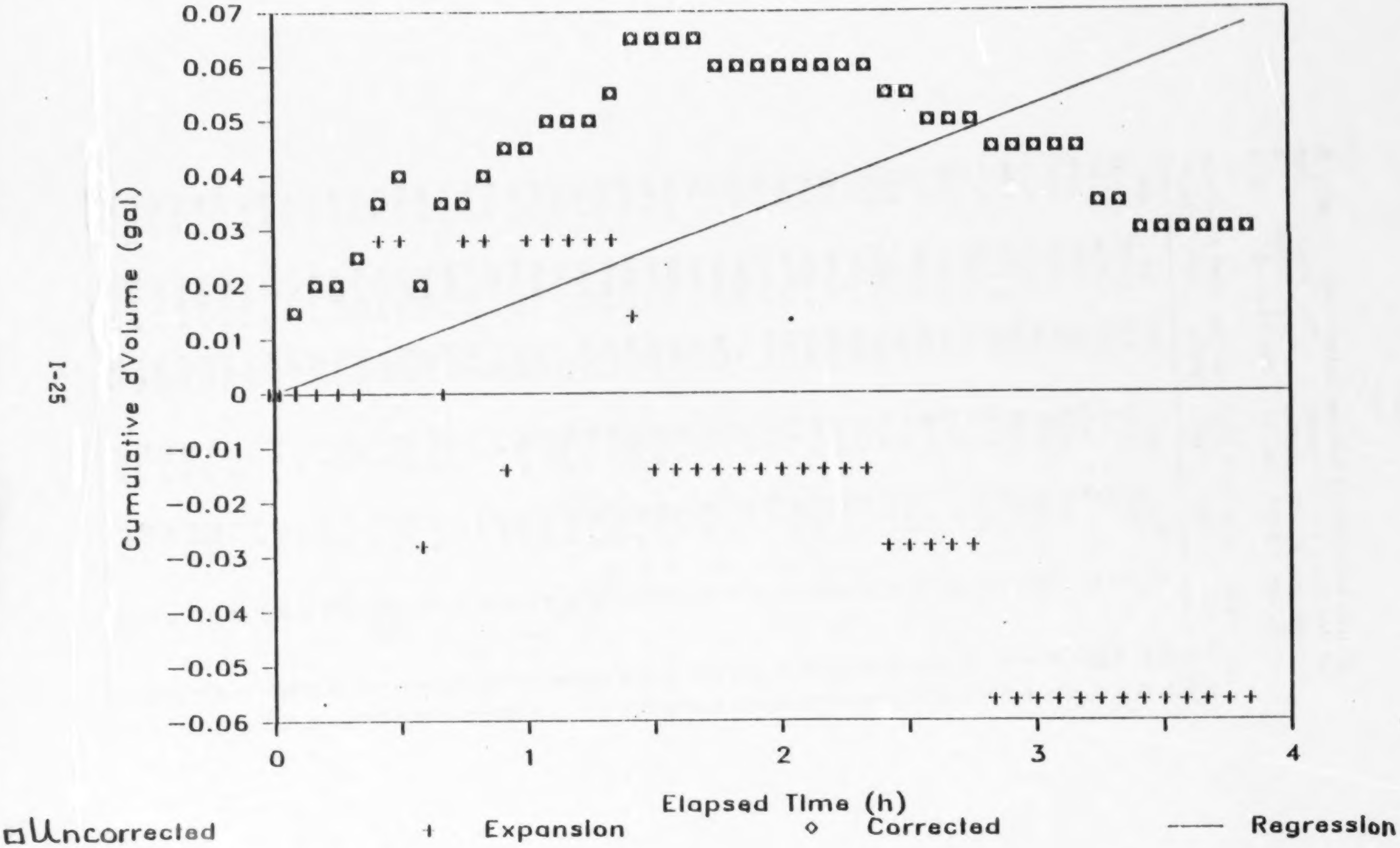
This test had a line that could not be certified because of a bad check valve.

The tank test data had some problems. There was a 25 minute gap in the data caused by the need to break concrete to isolate a line from the tank. A thermister box was giving erratic readings and had to be changed. When the thermister box was changed, there was a discontinuity in the temperature readings. Finally, there was an entry error in the data. To analyze the data, the erroneous entry was corrected, then only data taken after the thermister box was replaced were used. With these modifications, the data were adequate and the analysis satisfactory.

Form 8429-001SDS

LR	:Site Code	N310000109	Fuel Type	UNLEADED	Date	MAR.20,85
sig?	:Test Firm	O.H.M.	Tank Vol	7716	T digits	15567
N Y	:Test Crew	BS,DP,JS	API Dens	57.2	T digits/F	326
*	MRI Crew	W.B.,S.R.	Exp Coef	0.00059372	Leak Rate	0.018

Time Hr	Min	Level (div)	V Before (gal)	V After (gal)	Fuel Temp (digits)	Tcorr dV (gal)	Leak Rate (gal/h)
15	40	12	N/A	N/A	15567	N/A	N/A
15	45	12	0.540	0.555	15567	0.01500	0.180
15	50	12	0.555	0.56	15567	0.00500	0.060
15	55	12	0.56	0.56	15567	0.00000	0.000
16	0	12	0.56	0.565	15567	0.00500	0.060
16	5	12	0.565	0.575	15569	-0.01811	-0.217
16	10	12	0.575	0.58	15569	0.00500	0.060
16	15	12	0.185	0.165	15565	0.03621	0.435
16	20	12	0.165	0.18	15567	-0.01311	-0.157
16	25	12	0.18	0.18	15569	-0.02811	-0.337
16	30	12	0.18	0.185	15569	0.00500	0.060
16	35	12	0.185	0.19	15566	0.04716	0.566
16	40	12	0.19	0.19	15569	-0.04216	-0.506
16	45	12	0.19	0.195	15569	0.00500	0.060
16	50	12	0.195	0.195	15569	0.00000	0.000
16	55	12	0.195	0.195	15569	0.00000	0.000
17	0	12	0.195	0.2	15569	0.00500	0.060
17	5	12	0.2	0.21	15568	0.02405	0.289
17	10	12	0.21	0.21	15566	0.02811	0.337
17	15	12	0.21	0.21	15566	0.00000	0.000
17	20	12	0.21	0.21	15566	0.00000	0.000
17	25	12	0.21	0.205	15566	-0.00500	-0.060
17	30	12	0.205	0.205	15566	0.00000	0.000
17	35	12	0.205	0.205	15566	0.00000	0.000
17	40	12	0.205	0.205	15566	0.00000	0.000
17	45	12	0.205	0.205	15566	0.00000	0.000
17	50	12	0.205	0.205	15566	0.00000	0.000
17	55	12	0.205	0.205	15566	0.00000	0.000
18	0	12	0.205	0.205	15566	0.00000	0.000
18	5	12	0.205	0.2	15565	0.00905	0.109
18	10	12	0.2	0.2	15565	0.00000	0.000
18	15	12	0.2	0.195	15565	-0.00500	-0.060
18	20	12	0.195	0.195	15565	0.00000	0.000
18	25	12	0.195	0.195	15565	0.00000	0.000
18	30	12	0.195	0.19	15563	0.02311	0.277
18	35	12	0.19	0.19	15563	0.00000	0.000
18	40	12	0.19	0.19	15563	0.00000	0.000
18	45	12	0.31	0.31	15563	0.00000	0.000
18	50	12	0.31	0.31	15563	0.00000	0.000
18	55	12	0.31	0.3	15563	-0.01000	-0.120
19	0	12	0.3	0.3	15563	0.00000	0.000
19	5	12	0.3	0.295	15563	-0.00500	-0.060
19	10	12	0.295	0.295	15563	0.00000	0.000
19	15	12	0.295	0.295	15563	0.00000	0.000
19	20	12	0.295	0.295	15563	0.00000	0.000
19	25	12	0.295	0.295	15563	0.00000	0.000
19	30	12	0.295	0.295	15563	0.00000	0.000


Cumulative dVolume (gal)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
−0.01
−0.02
−0.03
−0.04
−0.05
−0.06
0
1
2
3
4
Elapsed Time (h)
□ Uncorrected
+ Expansion
◇ Corrected
— Regression

SITE DATA SUMMARY

Survey ID No. L310000557

Tank No. 1 of 1

Tank Size 1036 Gal.

Test Date Mar 21, 1985

Product Premium Unleaded

TEST RESULTS

	System	Line 1	Line 2	Line 3	Line 4
Certified	Yes	No	---		
Rate	-0.012	BCV			
S.E.	0.024	---			

Notes:

The line test found a bad check valve, so no rate could be estimated.

```
02-Apr-85                          Page 1


  LR  |Site Code L310000557 Fuel Type PREMIUM UNLDate      MAR.21.85
 sig? |Test Firm OHM        Tank Vol            1036 T digits      14373
 N  Y |Test Crew JS,DP,RS   API Dens            53.2 T digits/F      326
    *  MRI Crew  WB,SR      Exp Coef  0.00056532 Leak Rate       0.021

 Time    Level      V Before  V After   Fuel Temp  Tcorr dV Leak Rate
Hr  Min  (div)       (gal)     (gal)    (digits)    (gal)    (gal/h)
----------------------------------------------------------------------
12  50           12    N/A       N/A        14740    N/A        N/A
12  55           12    0.685     0.720      14752    0.013      0.161
13   0           12     0.72      0.75      14768    0.001      0.015
13   5           12     0.75      0.79      14794   -0.007     -0.081
13  10           12     0.79     0.825      14806    0.013      0.161
13  15           12    0.825     0.855      14823   -0.001     -0.006
13  20           12    0.855      0.89      14838    0.008      0.097
13  25           12     0.89      0.92      14852    0.005      0.058
13  30           12     0.92      0.95      14863    0.010      0.123
13  35           12    0.155      0.19      14887   -0.008     -0.097
13  40           12     0.19      0.22      14904   -0.001     -0.006
13  45           12     0.22      0.25      14923   -0.004     -0.050
13  50           12     0.25      0.28      14938    0.003      0.037
13  55           12     0.28       0.3      14948    0.002      0.024
14   0           12      0.3      0.33      14956    0.016      0.188
14   5           12     0.33     0.355      14968    0.003      0.041
14  10           12    0.355      0.38      14984   -0.004     -0.045
14  15           12     0.38       0.4      15001   -0.011     -0.126
14  20           12      0.4     0.435      15011    0.017      0.204
14  25           12    0.435      0.46      15027   -0.004     -0.045
14  30           12     0.46      0.48      15042   -0.007     -0.083
14  35           12    0.485     0.515      15056    0.005      0.058
14  40           12    0.515      0.54      15076   -0.011     -0.131
14  45           12     0.54      0.57      15084    0.015      0.188
14  50           12     0.57      0.59      15099   -0.007     -0.083
14  55           12     0.59      0.62      15125   -0.017     -0.201
15   0           12     0.62      0.64      15131    0.009      0.111
15   5           12     0.64      0.66      15130    0.022      0.262
15  10           12     0.66     0.685      15136    0.014      0.171
15  15           12    0.685       0.7      15152   -0.014     -0.165
15  20           12      0.7      0.72      15167   -0.007     -0.083
15  25           12     0.72      0.75      15178    0.010      0.123
15  30           12     0.75      0.76      15190   -0.012     -0.139
15  40           12     0.79      0.81      15212   -0.020     -0.117
15  45           12     0.02      0.04      15217    0.011      0.132
15  50           12     0.04      0.06      15224    0.007      0.089
15  55           12     0.06     0.085      15235    0.005      0.063
16   0           12    0.085     0.105      15240    0.011      0.132
16   5           12    0.105     0.125      15246    0.009      0.111
16  10           12    0.125     0.145      15256    0.002      0.024
16  15           12    0.145      0.13      15264   -0.029     -0.352
16  20           12     0.13     0.145      15273   -0.001     -0.014
16  25           12    0.145      0.16      15280    0.002      0.029
16  30           12     0.16      0.18      15298    0.006      0.068
16  35           12     0.18     0.195      15297   -0.001     -0.014
16  40           12    0.195      0.21      15304    0.002      0.029
16  45           12     0.21      0.22      15311   -0.003     -0.031
16  50           12     0.22      0.24      15319    0.006      0.068
```

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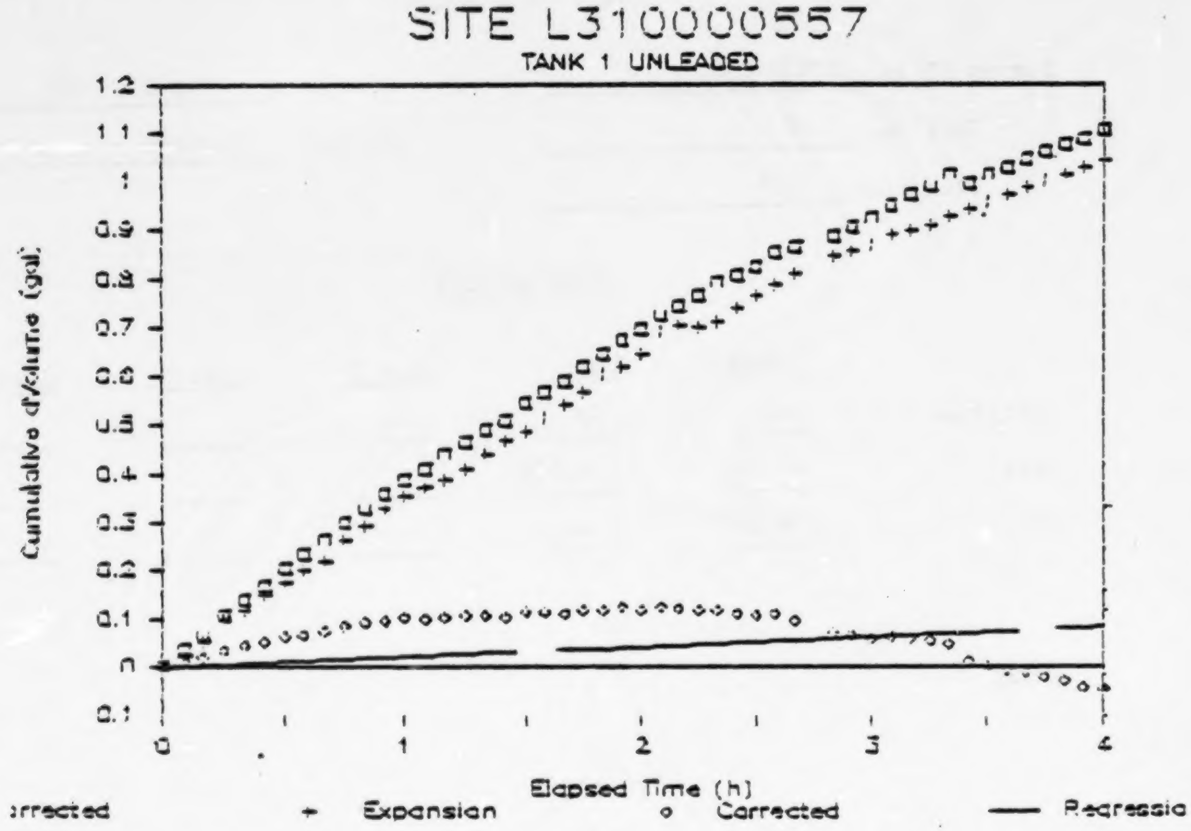

SITE L310000557
TANK 1 UNLEADED
Cumulative dVolume (gal)
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
0
1
2
3
4
Elapsed Time (h)
rrected
+ Expansion
o Corrected
— Regressio

SITE DATA SUMMARY

Survey ID No. L310000561

Test Date Mar 24, 1985

Tank No. 1 of 4

Product Unleaded

Tank Size 1034

TEST RESULTS

	System	Line 1	Line 2	Line 3	Line 4
Certified	Yes	No	---		
Rate	-0.036	-0.039			
S.E.	0.010	---			

Notes:

Form 8429-001SDS

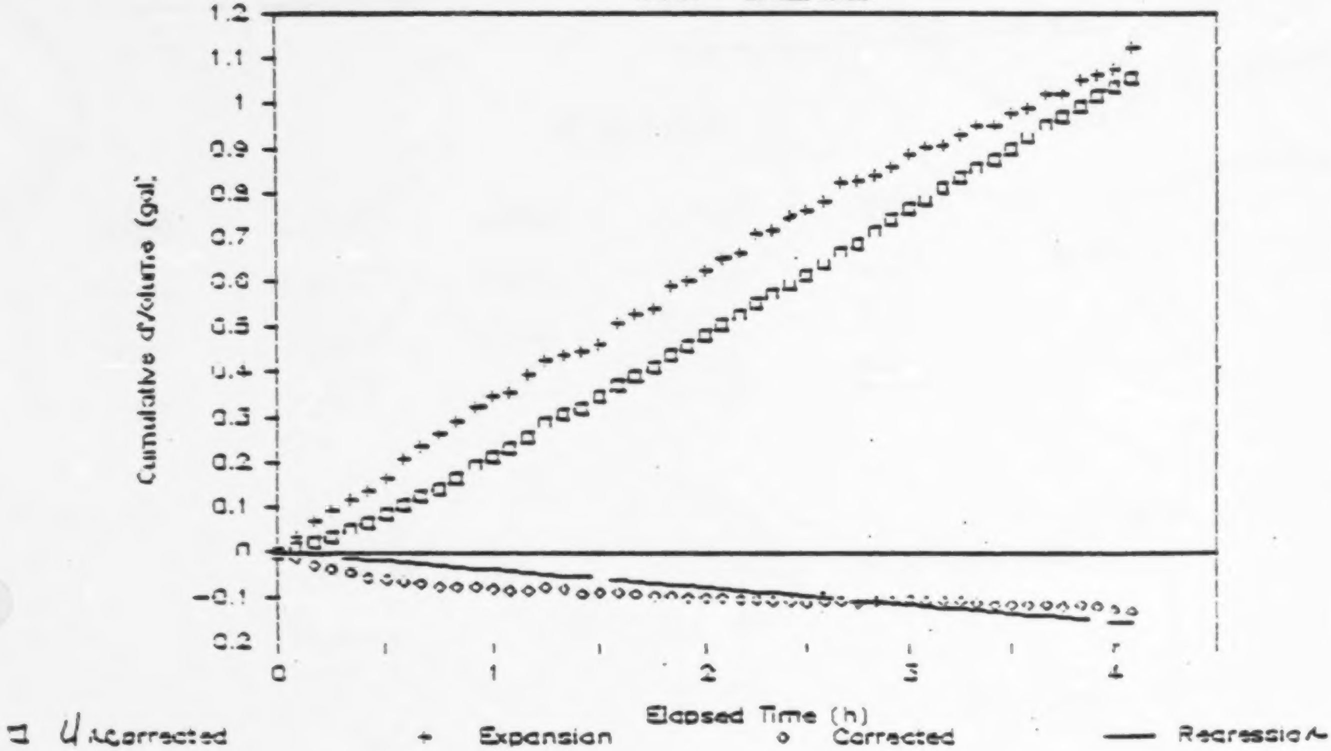
```
  LR  |Site Code L310000561 Fuel Type UNLEADED    Date        MAR 24,85
 sig? |Test Firm OHM        Tank Vol           1034 T digits        14092
 N  Y |Test Crew RS,JS,DP   API Dens           53.3 T digits/F        326
    *  MRI Crew  SR,WB      Exp Coef 0.00056603 Leak Rate       -0.039

 Time    Level      V Before  V After    Fuel Temp  Tcorr dV Leak Rate
Hr  Min  (div)       (gal)     (gal)     (digits)    (gal)    (gal/h)
-----------------------------------------------------------------------
10  45         12     N/A       N/A          14344    N/A       N/A
10  50         12      0.660     0.670       14362    -0.022    -0.268
10  55         12       0.67      0.68       14382    -0.026    -0.311
11   0         12       0.68     0.695       14397    -0.012    -0.143
11   5         12      0.695      0.71       14409    -0.007    -0.079
11  10         12       0.71     0.725       14420    -0.005    -0.057
11  15         12      0.725     0.745       14435    -0.007    -0.083
11  20         12      0.745     0.765       14459    -0.023    -0.277
11  25         12       0.61      0.63       14475    -0.009    -0.105
11  30         12       0.63     0.645       14490    -0.012    -0.143
11  35         12      0.645      0.67       14507    -0.006    -0.066
11  40         12       0.67     0.695       14524    -0.006    -0.066
11  45         12      0.695     0.715       14536    -0.002    -0.019
11  50         12      0.715     0.735       14541     0.011     0.132
11  55         12      0.735      0.76       14562    -0.013    -0.152
12   0         12       0.76      0.79       14581    -0.004    -0.049
12   5         12       0.79      0.81       14588     0.007     0.089
12  10         12       0.81     0.825       14592     0.008     0.094
12  15         12       0.41     0.435       14600     0.011     0.129
12  20         12      0.435      0.46       14625    -0.022    -0.250
12  25         12       0.46      0.48       14638    -0.002    -0.019
12  30         12       0.48       0.5       14645     0.007     0.089
12  35         12        0.5     0.525       14672    -0.023    -0.292
12  40         12      0.525     0.545       14679     0.007     0.089
12  45         12      0.545      0.57       14692     0.002     0.020
12  50         12       0.57     0.595       14709    -0.006    -0.066
12  55         12      0.595     0.615       14714     0.011     0.132
13   0         12      0.615      0.64       14739    -0.020    -0.239
13   5         12       0.64      0.66       14744     0.011     0.132
13  10         12       0.66     0.685       14761    -0.006    -0.066
13  15         12      0.685     0.705       14767     0.009     0.111
13  20         12      0.705      0.73       14779     0.003     0.041
13  25         12       0.73     0.755       14802    -0.016    -0.196
13  30         12       0.15      0.17       14805     0.015     0.175
13  35         12       0.17       0.2       14811     0.019     0.231
13  40         12        0.2     0.225       14822     0.005     0.063
13  45         12      0.225      0.25       14839    -0.006    -0.066
13  50         12       0.25      0.27       14847     0.006     0.068
13  55         12       0.27     0.295       14848     0.023     0.279
14   0         12      0.295      0.32       14862      .000    -0.002
14   5         12       0.32      0.34       14872     0.002     0.025
14  10         12       0.34      0.36       14872     0.020     0.240
14  15         12       0.36     0.385       14888    -0.004    -0.045
14  20         12      0.385      0.41       14896     0.011     0.128
14  25         12       0.41     0.435       14913    -0.006    -0.066
14  30         12      0.435     0.455       14912     0.022     0.262
14  35         12      0.455      0.48       14930    -0.007    -0.088
```

14	40	12	0.48	0.5	14936	0.009	0.111
14	45	12	0.5	0.52	14943	0.007	0.089
14	50	12	0.52	0.54	14969	-0.027	-0.320

SITE L310000561

TANK 1 UNLEADED



SITE DATA SUMMARY

Survey ID No. L310000561

Test Date Mar 23, 1985

Tank No. 2 of 4

Product Diesel

Tank Size 7896 Gal.

TEST RESULTS

	System	Line 1	Line 2	Line 3	Line 4
Certified	No	No	---		
Rate	-1.38	-0.065			
S.E.	0.049	---			

Notes:

This appears to be a bad leak.

Form 8429-001SDS

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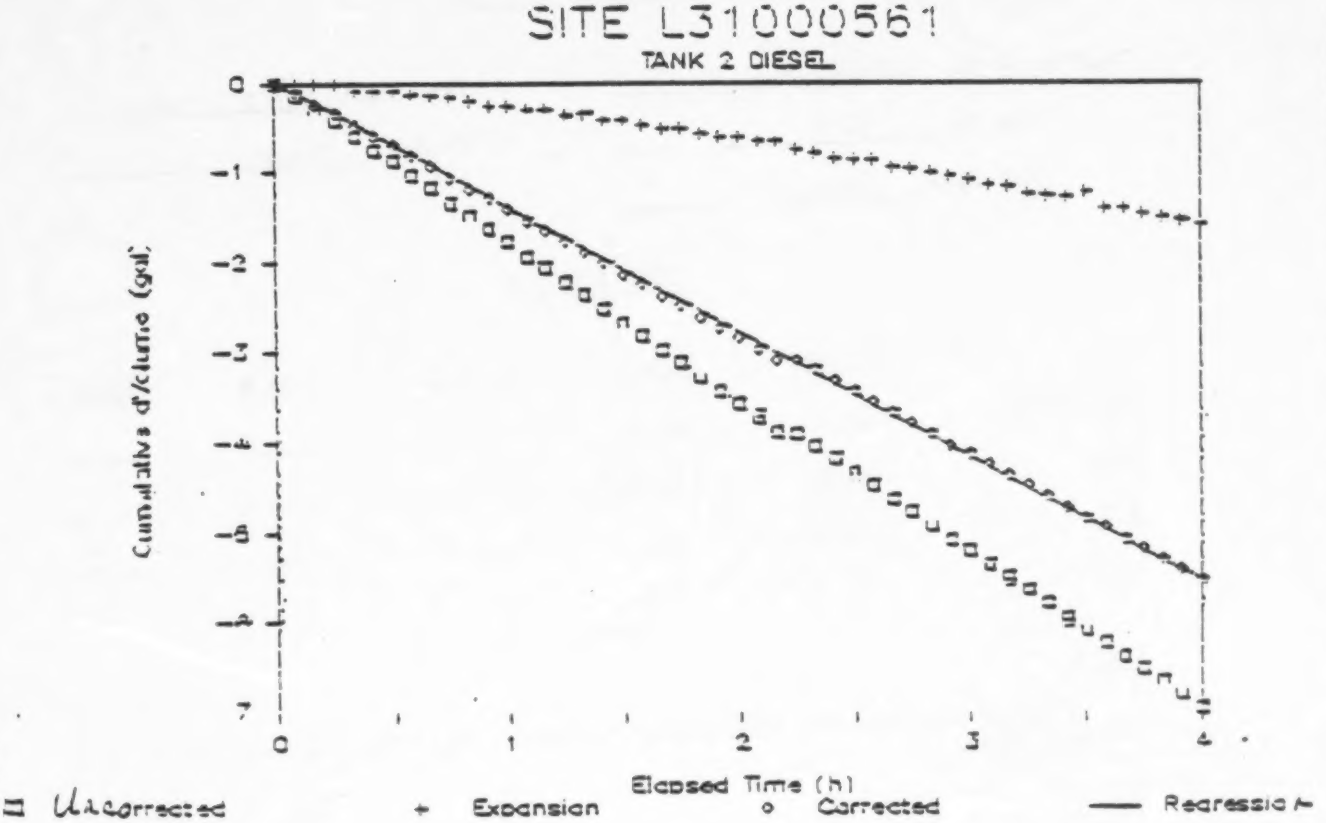
08-Apr-85                        Page 1

  LR  |Site Code L310000561 Fuel Type DIESEL      Date       MAR 23.85
 sig7 |Test Firm OHM        Tank Vol        7895 T digits       17510
 N  Y |Test Crew JS,DP,RS   API Dens        33.7 T digits/F       319
    *  MRI Crew  SR,WB      Exp Coef  0.00045255 Leak Rate     -1.385

 Time    Level      V Before  V After   Fuel Temp  Tcorr dV  Leak Rate
Hr  Min  (div)       (gal)     (gal)    (digits)    (gal)     (gal/h)
-----------------------------------------------------------------------
15  30          12     N/A       N/A          17430    N/A       N/A
15  35          12     0.600     0.460        17430   -0.140    -1.680
15  40          12      0.46      0.29        17430   -0.170    -2.040
15  45          12      0.88      0.75        17430   -0.120    -1.440
15  50          12      0.75     0.595        17423   -0.087    -1.039
15  55          12     0.595      0.44        17423   -0.155    -1.860
16   0          12      0.44     0.305        17423   -0.135    -1.620
16   5          12     0.305      0.16        17418   -0.089    -1.068
16  10          12      0.95       0.8        17417   -0.139    -1.666
16  15          12       0.8      0.64        17415   -0.138    -1.651
16  20          12      0.64     0.495        17412   -0.111    -1.337
16  25          12     0.495      0.35        17407   -0.089    -1.068
16  30          12      0.35     0.205        17407   -0.145    -1.740
16  35          12     0.935     0.775        17403   -0.115    -1.382
16  40          12     0.775     0.645        17403   -0.130    -1.560
16  45          12     0.645     0.485        17397   -0.093    -1.113
16  50          12     0.485     0.345        17397   -0.140    -1.680
16  55          12     0.345      0.19        17392   -0.099    -1.198
17   0          12      0.19     0.035        17392   -0.155    -1.860
17   5          12      0.92      0.78        17388   -0.095    -1.142
17  10          12      0.78      0.62        17384   -0.115    -1.382
17  15          12      0.62      0.48        17384   -0.140    -1.680
17  20          12      0.48     0.325        17378   -0.088    -1.053
17  25          12     0.325     0.165        17375   -0.125    -1.517
17  30          12      0.96      0.83        17375   -0.130    -1.560
17  35          12      0.83      0.66        17371   -0.125    -1.502
17  40          12      0.66      0.52        17371   -0.140    -1.680
17  45          12      0.52     0.485        17362    0.066     0.790
17  50          12     0.485      0.35        17358   -0.091    -1.097
17  55          12      0.35     0.215        17353   -0.078    -0.933
18   0          12         1     0.845        17351   -0.133    -1.591
18   5          12     0.845      0.71        17351   -0.135    -1.620
18  10          12      0.71     0.555        17346   -0.088    -1.053
18  15          12     0.555     0.405        17343   -0.128    -1.531
18  20          12     0.405     0.255        17340   -0.116    -1.397
18  25          12     0.255     0.095        17336   -0.115    -1.382
18  30          12     0.995     0.875        17333   -0.086    -1.037
18  35          12     0.875     0.725        17327   -0.083    -0.993
18  40          12     0.725      0.58        17325   -0.123    -1.471
18  45          12      0.58      0.43        17319   -0.083    -0.993
18  50          12     0.735      0.58        17316   -0.121    -1.457
18  55          12      0.58      0.42        17314   -0.138    -1.651
19   0          12      0.42      0.27        17320   -0.217    -2.607
19   5          12         1      0.87        17305    0.038     0.457
19  10          12      0.87      0.71        17304   -0.149    -1.786
19  15          12      0.71      0.57        17299   -0.084    -1.008
19  20          12      0.57     0.435        17296   -0.101    -1.217
19  25          12     0.435     0.285        17292   -0.105    -1.252
```

19	30	12	0.285	0.14	17289	-0.111	-1.337


SITE L31000561
TANK 2 DIESEL
Cumulative Volume (gal)
0
-1
-2
-3
-4
-5
-6
-7
0
1
2
3
4
Elapsed Time (h)
□ Uncorrected
+ Expansion
○ Corrected
— Regression

SITE DATA SUMMARY

Survey ID No. L310000561

Tank No. 3 of 4

Tank Size 7869 Gal

Test Date Mar 23, 1985

Product Diesel

TEST RESULTS

	System	Line 1	Line 2	Line 3	Line 4
Certified	No	No	---		
Rate	-0.263	"Large"			
S.E.	0.014	--			

Notes:

Both the tank and line appear to leak. The line leak was not quantified.

Form 8429-001SDS

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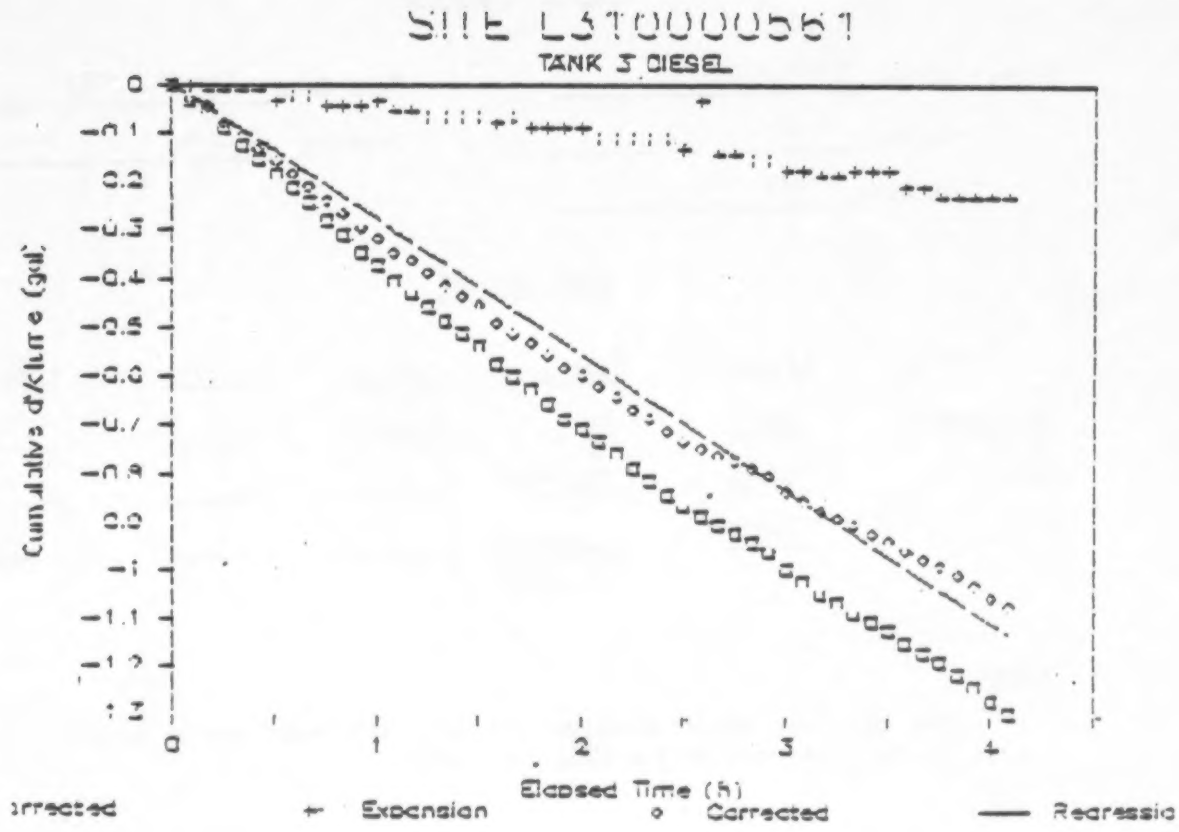
LR	Site Code L31000561	Fuel Type DIESEL		Date	MAR 23,85
sig?	Test Firm OHM	Tank Vol	7863	T digits	15082
N Y	Test Crew RS,JS,DP	API Dens	35.7	T digits/F	325
*	MRI Crew SR,WB	Exp Coef	0.00046165	Leak Rate	-0.277

Time Hr	Time Min	Level (div)	V Before (gal)	V After (gal)	Fuel Temp (digits)	Tcorr dV (gal)	Leak Rate (gal/h)
14	45	12	N/A	N/A	15054	N/A	N/A
14	50	12	0.430	0.395	15054	-0.035	-0.420
14	55	12	0.395	0.375	15053	-0.009	-0.106
15	0	12	0.375	0.34	15053	-0.035	-0.420
15	5	12	0.795	0.76	15053	-0.035	-0.420
15	10	12	0.76	0.73	15053	-0.030	-0.360
15	15	12	0.73	0.7	15051	-0.008	-0.093
15	20	12	0.7	0.67	15052	-0.041	-0.494
15	25	12	0.67	0.64	15052	-0.030	-0.360
15	30	12	0.64	0.605	15050	-0.013	-0.153
15	35	12	0.605	0.575	15050	-0.030	-0.360
15	40	12	0.575	0.54	15050	-0.035	-0.420
15	45	12	0.54	0.515	15051	-0.036	-0.434
15	50	12	0.515	0.48	15049	-0.013	-0.153
15	55	12	0.48	0.46	15049	-0.020	-0.240
16	0	12	0.46	0.43	15048	-0.019	-0.225
16	5	12	0.43	0.4	15048	-0.030	-0.360
16	10	12	0.4	0.375	15048	-0.025	-0.300
16	15	12	0.795	0.77	15048	-0.025	-0.300
16	20	12	0.77	0.73	15047	-0.029	-0.346
16	25	12	0.73	0.705	15048	-0.036	-0.434
16	30	12	0.705	0.68	15046	-0.003	-0.033
16	35	12	0.68	0.65	15046	-0.030	-0.360
16	40	12	0.65	0.62	15046	-0.030	-0.360
16	45	12	0.62	0.6	15046	-0.020	-0.240
16	50	12	0.6	0.575	15044	-0.003	-0.033
16	55	12	0.575	0.55	15044	-0.025	-0.300
17	0	12	0.55	0.52	15044	-0.030	-0.360
17	5	12	0.52	0.495	15044	-0.025	-0.300
17	10	12	0.495	0.465	15044	-0.030	-0.360
17	15	12	0.9	0.875	15042	-0.003	-0.033
17	20	12	0.875	0.855	15051	-0.120	-1.443
17	25	12	0.855	0.835	15041	0.091	1.097
17	30	12	0.835	0.82	15041	-0.015	-0.180
17	35	12	0.82	0.8	15040	-0.009	-0.106
17	40	12	0.8	0.78	15040	-0.020	-0.240
17	45	12	0.78	0.745	15038	-0.013	-0.153
17	50	12	0.745	0.72	15038	-0.025	-0.300
17	55	12	0.72	0.695	15037	-0.014	-0.166
18	0	12	0.695	0.675	15037	-0.020	-0.240
18	5	12	0.675	0.655	15038	-0.031	-0.374
18	10	12	0.655	0.635	15038	-0.020	-0.240
18	15	12	0.635	0.615	15038	-0.020	-0.240
18	20	12	0.615	0.59	15035	0.008	0.101
18	25	12	0.59	0.57	15035	-0.020	-0.240
18	30	12	0.57	0.55	15033	0.002	0.027
18	35	12	0.55	0.525	15033	-0.025	-0.300
18	40	12	0.525	0.5	15033	-0.025	-0.300

18	45	12	0.5	0.47	15033	-0.030	-0.360
18	50	12	0.47	0.445	15033	-0.025	-0.300


SITE L3T0000561
TANK 3 DIESEL
0
-0.1
0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
0.9
-1
-1.1
-1.2
1.3
Cumulative Volume (gal)
0
1
2
3
4
Elapsed Time (h)
orrected
+ Expansion
o Corrected
— Regressio

SITE DATA SUMMARY

Survey ID No. L310000561

Test Date Mar 24, 1985

Tank No. 4 of 4

Product Diesel

Tank Size 10152

TEST RESULTS

	System	Line 1	Line 2	Line 3	Line 4
Certified	Yes	No	---		
Rate	0.009	"Large"			
S.E.	0.0107	---			

Notes:

The line test report included the note that there was a "large" leak in the line, but no quantitative number.

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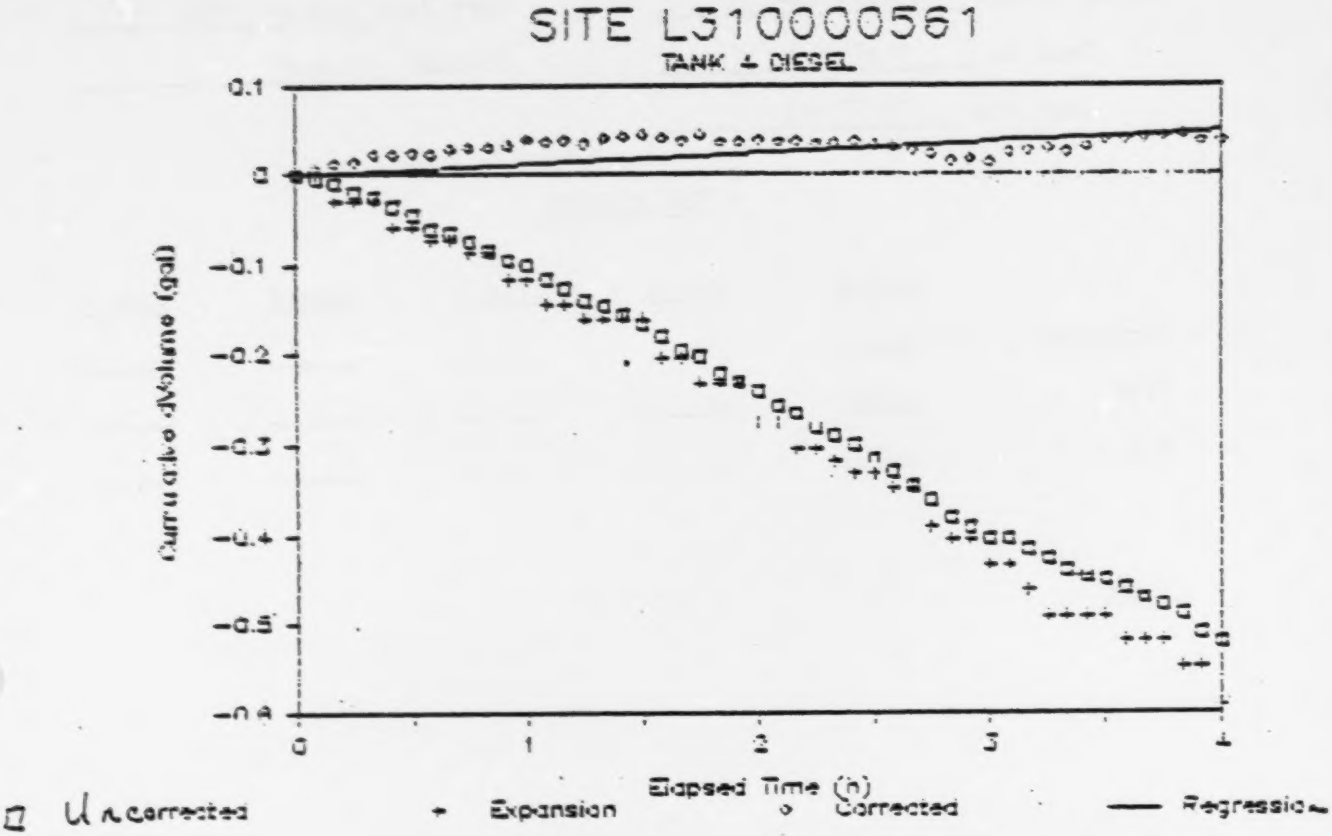
```
 LR  |Site Code L310000561 Fuel Type DIESEL      Date       MAR.24,85
sig? |Test Firm DHM        Tank Vol         10152 T digits       14636
N  Y |Test Crew JS,DP,RS   API Dens          36.1 T digits/F       325
   *  MRI Crew  SR,WB      Exp Coef  0.00046345 Leak Rate        0.012

 Time     Level      V Before  V After   Fuel Temp  Tcorr dV Leak Rate
Hr  Min   (div)       (gal)     (gal)    (digits)    (gal)    (gal/h)
-----------------------------------------------------------------------
15  35          12     N/A       N/A         14620    N/A       N/A
15  40          12     0.720     0.715       14620   -0.005    -0.060
15  45          12     0.715      0.71       14618    0.024     0.286
15  50          12      0.71       0.7       14618   -0.010    -0.120
15  55          12       0.7     0.695       14618   -0.005    -0.060
16   0          12     0.695     0.685       14616    0.019     0.225
16   5          12     0.685     0.675       14616   -0.010    -0.120
16  10          12     0.675      0.66       14615   -0.001    -0.007
16  15          12      0.66     0.655       14615   -0.005    -0.060
16  20          12     0.655     0.645       14614    0.004     0.053
16  25          12     0.645     0.635       14614   -0.010    -0.120
16  30          12     0.635     0.625       14612    0.019     0.225
16  35          12     0.625      0.62       14612   -0.005    -0.060
16  40          12      0.62     0.605       14610    0.014     0.166
16  45          12     0.605     0.595       14610   -0.010    -0.120
16  50          12     0.595      0.58       14609   -0.001    -0.007
16  55          12      0.58     0.575       14609   -0.005    -0.060
17   0          12     0.575     0.565       14609   -0.010    -0.120
17   5          12     0.565     0.555       14609   -0.010    -0.120
17  10          12     0.555      0.54       14606    0.028     0.340
17  15          12      0.54     0.525       14606   -0.015    -0.180
17  20          12     0.525      0.52       14604    0.024     0.286
17  25          12      0.52       0.5       14604   -0.020    -0.240
17  30          12       0.5      0.49       14604   -0.010    -0.120
17  35          12      0.49      0.48       14601    0.033     0.400
17  40          12      0.99     0.975       14601   -0.015    -0.180
17  45          12     0.975     0.965       14599    0.019     0.225
17  50          12     0.965      0.95       14599   -0.015    -0.180
17  55          12      0.95      0.94       14598    0.004     0.053
18   0          12      0.94      0.93       14597    0.004     0.053
18   5          12      0.93     0.915       14597   -0.015    -0.180
18  10          12     0.915       0.9       14596   -0.001    -0.007
18  15          12       0.9     0.885       14596   -0.015    -0.180
18  20          12     0.885      0.87       14593    0.028     0.340
18  25          12      0.87      0.85       14592   -0.006    -0.067
18  30          12      0.85      0.84       14592   -0.010    -0.120
18  35          12      0.84     0.825       14590    0.014     0.166
18  40          12     0.825     0.825       14590    0.000     0.000
18  45          12     0.825     0.815       14588    0.019     0.225
18  50          12     0.815     0.805       14586    0.019     0.225
18  55          12     0.805      0.79       14586   -0.015    -0.180
19   0          12      0.79     0.785       14586   -0.005    -0.060
19   5          12     0.785      0.78       14586   -0.005    -0.060
19  10          12      0.78      0.77       14584    0.019     0.225
19  15          12      0.77      0.76       14584   -0.010    -0.120
19  20          12      0.76      0.75       14584   -0.010    -0.120
19  25          12      0.75      0.74       14582    0.019     0.225
19  30          12      0.74      0.72       14582   -0.020    -0.240
```

19 35	12	0.72	0.71	14579	0.033	0.400


SITE L310000561
TANK 4 DIESEL
Cumulative Volume (gal)
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
0
1
2
3
4
Elapsed Time (h)
□ Uncorrected
+ Expansion
◇ Corrected
— Regression

SITE DATA SUMMARY

Survey ID No. G310000464

Test Date Mar 29, 1985

Tank No. 1 of 3

Product Diesel

Tank Size 10152 Gal.

TEST RESULTS

	System	Line 1	Line 2	Line 3	Line 4
Certified	Yes	NA			
Rate	0.026	---			
S.E.	0.011				

Notes:

Form 8429-001SDS

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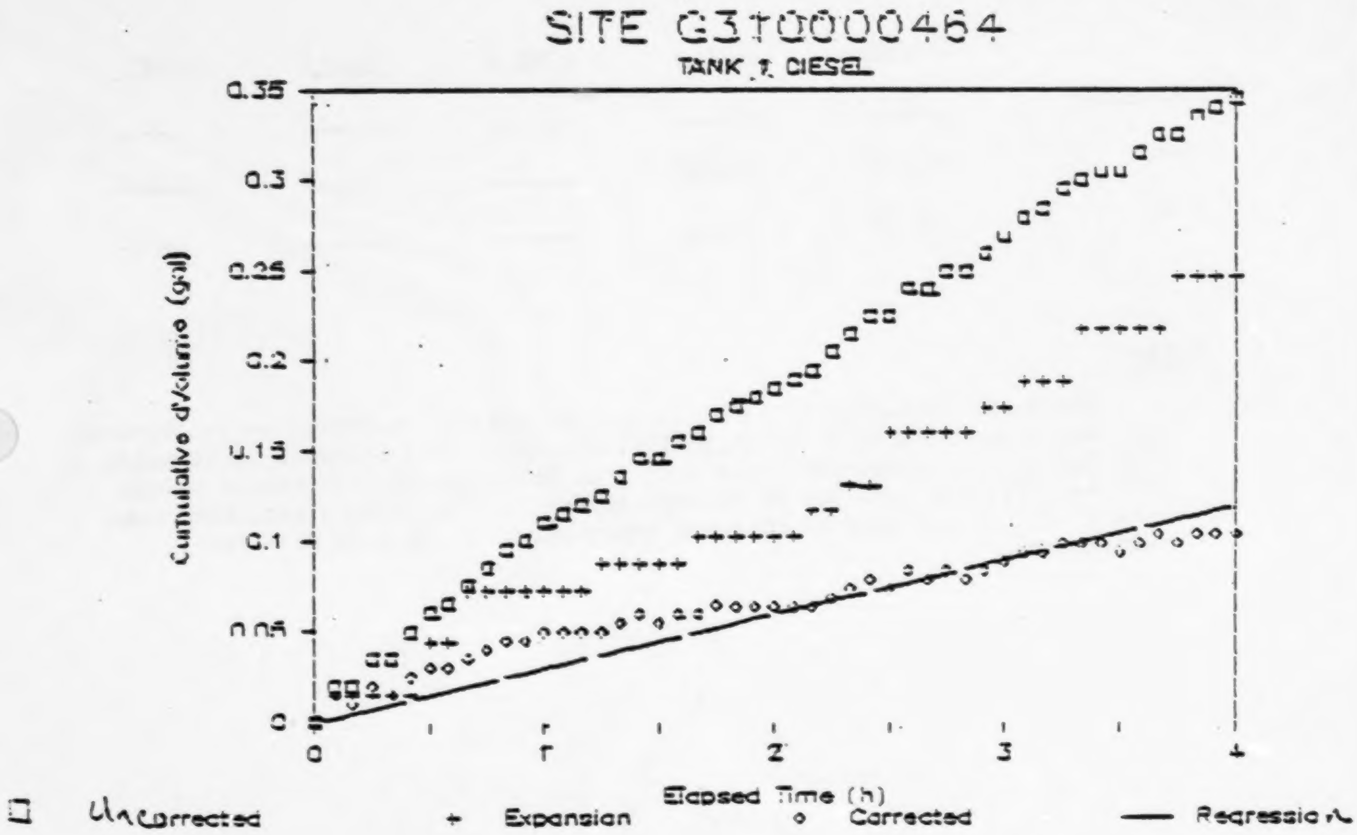
02-Apr-85                         Page 1

  LR  !Site Code G310000464 Fuel Type DIESEL      Date        MAR 28,1985
 sig? !Test Firm OHM        Tank Vol        10152 T digits          13884
 N  Y !Test Crew RS,JS,DP   API Dens         36.4 T digits/F          325
    •  MRI Crew  SR,WB      Exp Coef  0.0004648 Leak Rate         0.030

 Time     Level      V Before  V After   Fuel Temp  Tcorr dV Leak Rate
Hr  Min  (div)         (gal)     (gal)    (digits)    (gal)    (gal/h)
-----------------------------------------------------------------------
13  20           12     N/A       N/A         13889    N/A        N/A
13  25           12     0.805     0.825       13890    0.005     0.066
13  30           12     0.825     0.825       13890    0.000     0.000
13  35           12     0.825      0.84       13890    0.015     0.180
13  40           12      0.84      0.84       13890    0.000     0.000
13  45           12      0.84     0.855       13890    0.015     0.180
13  50           12     0.855     0.865       13892   -0.019    -0.228
13  55           12     0.865      0.87       13892    0.005     0.060
14   0           12      0.87      0.88       13894   -0.019    -0.228
14   5           12      0.88      0.89       13894    0.010     0.120
14  10           12      0.89       0.9       13894    0.010     0.120
14  15           12       0.9     0.905       13894    0.005     0.060
14  20           12     0.905     0.915       13894    0.010     0.120
14  25           12     0.915      0.92       13894    0.005     0.060
14  30           12      0.29     0.295       13894    0.005     0.060
14  35           12     0.295       0.3       13895   -0.010    -0.114
14  40           12       0.3      0.31       13895    0.010     0.120
14  45           12      0.31      0.32       13895    0.010     0.120
14  50           12      0.32      0.32       13895    0.000     0.000
14  55           12      0.32      0.33       13895    0.010     0.120
15   0           12      0.33     0.335       13896   -0.010    -0.114
15   5           12     0.335     0.345       13896    0.010     0.120
15  10           12     0.345      0.35       13896    0.005     0.060
15  15           12      0.35     0.355       13896    0.005     0.060
15  20           12     0.355      0.36       13896    0.005     0.060
15  25           12      0.36     0.365       13896    0.005     0.060
15  30           12     0.365      0.37       13897   -0.010    -0.114
15  35           12      0.37      0.38       13897    0.010     0.120
15  40           12      0.38      0.39       13898   -0.005    -0.054
15  45           12      0.39       0.4       13898    0.010     0.120
15  50           12       0.4       0.4       13900   -0.029    -0.348
15  55           12       0.4     0.415       13900    0.015     0.180
16   0           12     0.415     0.415       13900    0.000     0.000
16   5           12     0.415     0.425       13900    0.010     0.120
16  10           12     0.425     0.425       13900    0.000     0.000
16  15           12     0.425     0.435       13901   -0.005    -0.054
16  20           12     0.435     0.445       13901    0.010     0.120
16  25           12     0.445     0.455       13902   -0.005    -0.054
16  30           12     0.455      0.46       13902    0.005     0.060
16  35           12      0.46      0.47       13902    0.010     0.120
16  40           12      0.47     0.475       13904   -0.024    -0.298
16  45           12     0.475      0.48       13904    0.005     0.060
16  50           12      0.48      0.48       13904    0.000     0.000
16  55           12      0.48      0.49       13904    0.010     0.120
17   0           12      0.49       0.5       13904    0.010     0.120
17   5           12       0.5       0.5       13906   -0.029    -0.348
17  10           12       0.5      0.51       13906    0.010     0.120
17  15           12      0.51     0.515 I-46  13906    0.005     0.060
```

17	20	12	0.515	0.52	13906	0.005	0.060


SITE G310000464
TANK 1 DIESEL
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Cumulative d'Volume (gal)
0
1
2
3
4
Elapsed Time (h)
□ Uncorrected
+ Expansion
○ Corrected
— Regression

SITE DATA SUMMARY

Survey ID No. G310000464　　Test Date Mar 27, 1985

Tank No. 2 of 3　　Product Diesel

Tank Size 10152

TEST RESULTS

	System	Line 1	Line 2	Line 3	Line 4
Certified	No	No			
Rate	-0.107	-0.007			
S.E.	0.0041	---			

Notes:

There was virtually no level change throughout the entire test. However, the temperature seemed to be slightly increasing. The increase in temperature reported by the thermister would mean that there should have been a volume increase over the test due to thermal expansion. The entire estimated leak rate is due to the lack of observed expansion to correspond with the temperature.

Form 3429-001SDS

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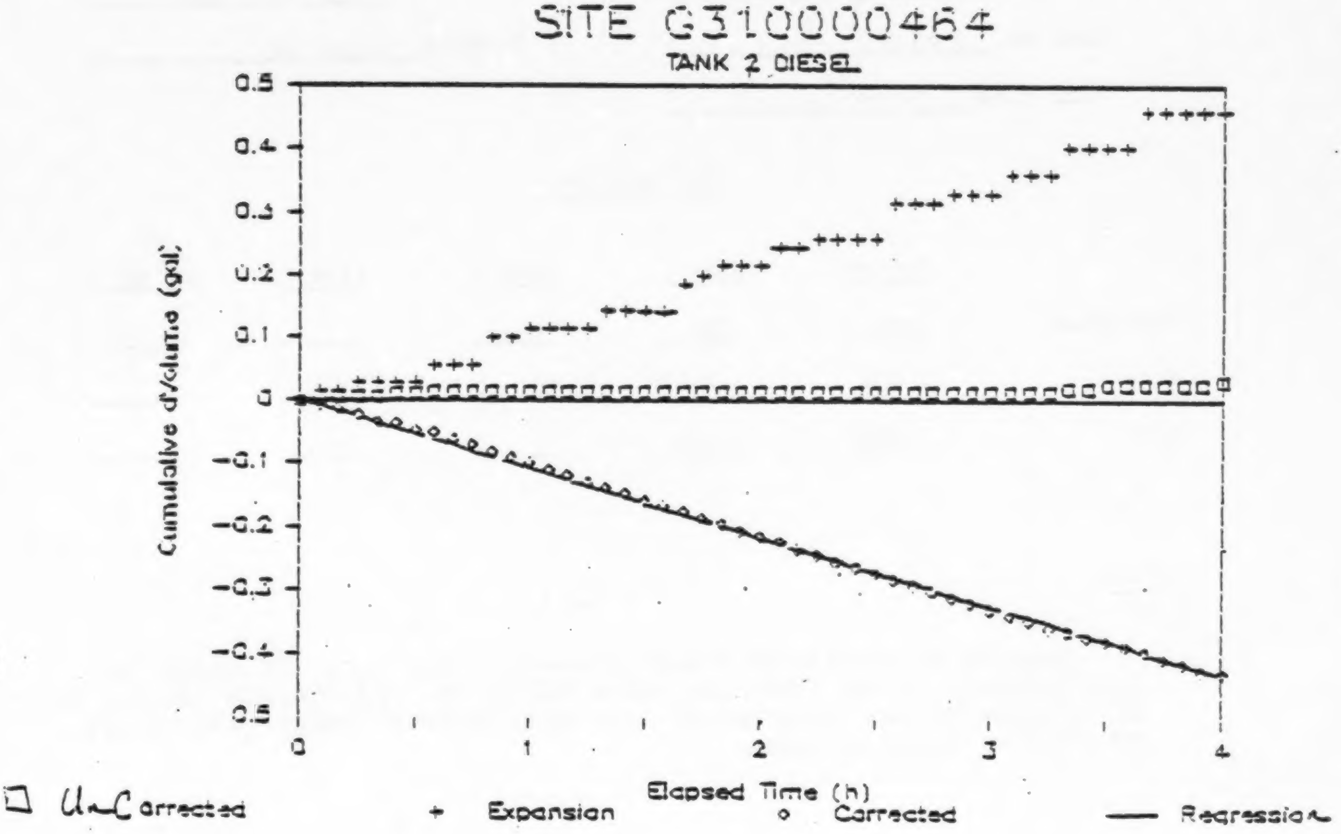
LR	Site Code	6310000464	Fuel Type	DIESEL	Date	MAR 27,1985
sig?	Test Firm	OHM	Tank Vol	10152	T digits	14310
N Y	Test Crew	RS,JS,DP	API Dens	35.7	T digits/F	325
•	MRI Crew	SR,WB	Exp Coef	0.00046165	Leak Rate	-0.108

Time Hr	Time Min	Level (div)	V Before (gal)	V After (gal)	Fuel Temp (digits)	Tcorr dV (gal)	Leak Rate (gal/h)
17	15	12	N/A	N/A	14331	N/A	N/A
17	20	12	0.880	0.880	14332	-0.014	-0.173
17	25	12	0.88	0.885	14332	0.005	0.060
17	30	12	0.885	0.885	14333	-0.014	-0.173
17	35	12	0.885	0.885	14333	0.000	0.000
17	40	12	0.885	0.89	14333	0.005	0.060
17	45	12	0.89	0.89	14333	0.000	0.000
17	50	12	0.89	0.895	14335	-0.024	-0.285
17	55	12	0.895	0.895	14335	0.000	0.000
18	0	12	0.895	0.895	14335	0.000	0.000
18	5	12	0.895	0.895	14338	-0.043	-0.518
18	10	12	0.895	0.895	14338	0.000	0.000
18	15	12	0.895	0.895	14339	-0.014	-0.173
18	20	12	0.895	0.895	14339	0.000	0.000
18	25	12	0.895	0.895	14339	0.000	0.000
18	30	12	0.895	0.895	14339	0.000	0.000
18	35	12	0.895	0.895	14341	-0.029	-0.345
18	40	12	0.895	0.895	14341	0.000	0.000
18	45	12	0.895	0.895	14341	0.000	0.000
18	50	12	0.895	0.895	14341	0.000	0.000
18	55	12	0.895	0.895	14344	-0.043	-0.518
19	0	12	0.895	0.895	14345	-0.014	-0.173
19	5	12	0.895	0.895	14346	-0.014	-0.173
19	10	12	0.895	0.895	14346	0.000	0.000
19	15	12	0.895	0.895	14346	0.000	0.000
19	20	12	0.895	0.895	14348	-0.029	-0.345
19	25	12	0.895	0.895	14348	0.000	0.000
19	30	12	0.895	0.895	14349	-0.014	-0.173
19	35	12	0.895	0.895	14349	0.000	0.000
19	40	12	0.895	0.895	14349	0.000	0.000
19	45	12	0.895	0.895	14349	0.000	0.000
19	50	12	0.895	0.895	14353	-0.058	-0.690
19	55	12	0.895	0.895	14353	0.000	0.000
20	0	12	0.895	0.895	14353	0.000	0.000
20	5	12	0.895	0.895	14354	-0.014	-0.173
20	10	12	0.895	0.895	14354	0.000	0.000
20	15	12	0.895	0.895	14354	0.000	0.000
20	20	12	0.895	0.895	14356	-0.029	-0.345
20	25	12	0.895	0.895	14356	0.000	0.000
20	30	12	0.895	0.895	14356	0.000	0.000
20	35	12	0.895	0.9	14359	-0.038	-0.458
20	40	12	0.9	0.9	14359	0.000	0.000
20	45	12	0.9	0.905	14359	0.005	0.060
20	50	12	0.905	0.905	14359	0.000	0.000
20	55	12	0.905	0.905	14363	-0.058	-0.690
21	0	12	0.905	0.905	14363	0.000	0.000
21	5	12	0.905	0.905	14363	0.000	0.000
21	10	12	0.905	0.905	14363	0.000	0.000

21	15	12	0.905	0.91	14363	0.005	0.060


SITE G310000464
TANK 2 DIESEL
Cumulative d'olume (gal)
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
1
2
3
4
Elapsed Time (h)
☐ Un Corrected
+ Expansion
○ Corrected
— Regression

SITE DATA SUMMARY

Survey ID No. G310000464

Tank No. 3 of 3

Tank Size 10152

Test Date Mar 28, 1985

Product Unleaded

TEST RESULTS

	System	Line 1	Line 2	Line 3	Line 4
Certified	Yes	Yes	---		
Rate	0.052	-0.017			
S.E.	0.0047	---			

Notes:

There is an unexplained volume increase in this test. It appears to occur primarily in the first hour and a half or so. That is, the temperature was constant for the first period, then began to drift upward, parallelling the observed volume increase.

Form 8429-001SDS

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05-Jun-85                              Page 1

  LR   :Site Code G310000464 Fuel Type UNLEADED    Date        MAR 28,85
 sig?  :Test Firm OHM        Tank Vol          10152 T digits        14680
 N  Y  :Test Crew RS,JS,DP   API Dens           55.3 T digits/F        326
    *   MRI Crew  SR,WB      Exp Coef   0.00058023 Leak Rate         0.010

 Time     Level      V Before  V After    Fuel Temp   Tcorr dV Leak Rate
Hr  Min   (div)        (gal)     (gal)     (digits)     (gal)    (gal/h)
--------------------------------------------------------------------------
13  10          12     N/A        N/A          14723      N/A        N/A
13  15          12      0.535      0.555       14725     -0.016     -0.194
13  20          12      0.555       0.57       14726     -0.003     -0.037
13  25          12       0.57      0.585       14727     -0.003     -0.037
13  30          12      0.585        0.6       14727      0.015      0.180
13  35          12        0.6       0.61       14727      0.010      0.120
13  40          12       0.61       0.62       14728     -0.008     -0.097
13  45          12       0.62       0.63       14729     -0.008     -0.097
13  50          12       0.63       0.65       14730      0.002      0.023
13  55          12       0.65      0.665       14731     -0.003     -0.037
14   0          12      0.665      0.685       14731      0.020      0.240
14   5          12      0.685        0.7       14731      0.015      0.180
14  10          12        0.7       0.72       14733     -0.016     -0.194
14  15          12      0.695       0.71       14734     -0.003     -0.037
14  20          12       0.71      0.725       14735     -0.003     -0.037
14  25          12      0.725      0.745       14736      0.002      0.023
14  30          12      0.745      0.765       14737      0.002      0.023
14  35          12      0.765       0.78       14737      0.015      0.180
14  40          12       0.78      0.795       14738     -0.003     -0.037
14  45          12      0.795       0.81       14738      0.015      0.180
14  50          12       0.81       0.83       14740     -0.016     -0.194
14  55          12       0.83       0.85       14742     -0.016     -0.194
15   0          12       0.85      0.865       14743     -0.003     -0.037
15   5          12      0.865      0.885       14744      0.002      0.023
15  10          12        0.3       0.31       14744      0.010      0.120
15  15          12       0.31      0.325       14745     -0.003     -0.037
15  20          12      0.325       0.33       14745      0.005      0.060
15  25          12       0.33       0.35       14745      0.020      0.240
15  30          12       0.35       0.37       14746      0.002      0.023
15  35          12       0.37       0.39       14748     -0.016     -0.194
15  40          12       0.39        0.4       14748      0.010      0.120
15  45          12        0.4      0.415       14748      0.015      0.180
15  50          12      0.415      0.435       14750     -0.016     -0.194
15  55          12      0.435      0.455       14750      0.020      0.240
16   0          12      0.455       0.48       14752     -0.011     -0.134
16   5          12       0.48      0.495       14752      0.015      0.180
16  10          12      0.495      0.515       14752      0.020      0.240
16  15          12      0.515      0.535       14754     -0.016     -0.194
16  20          12      0.535       0.55       14756     -0.021     -0.254
16  25          12       0.55      0.555       14756      0.005      0.060
16  30          12      0.555       0.57       14756      0.015      0.180
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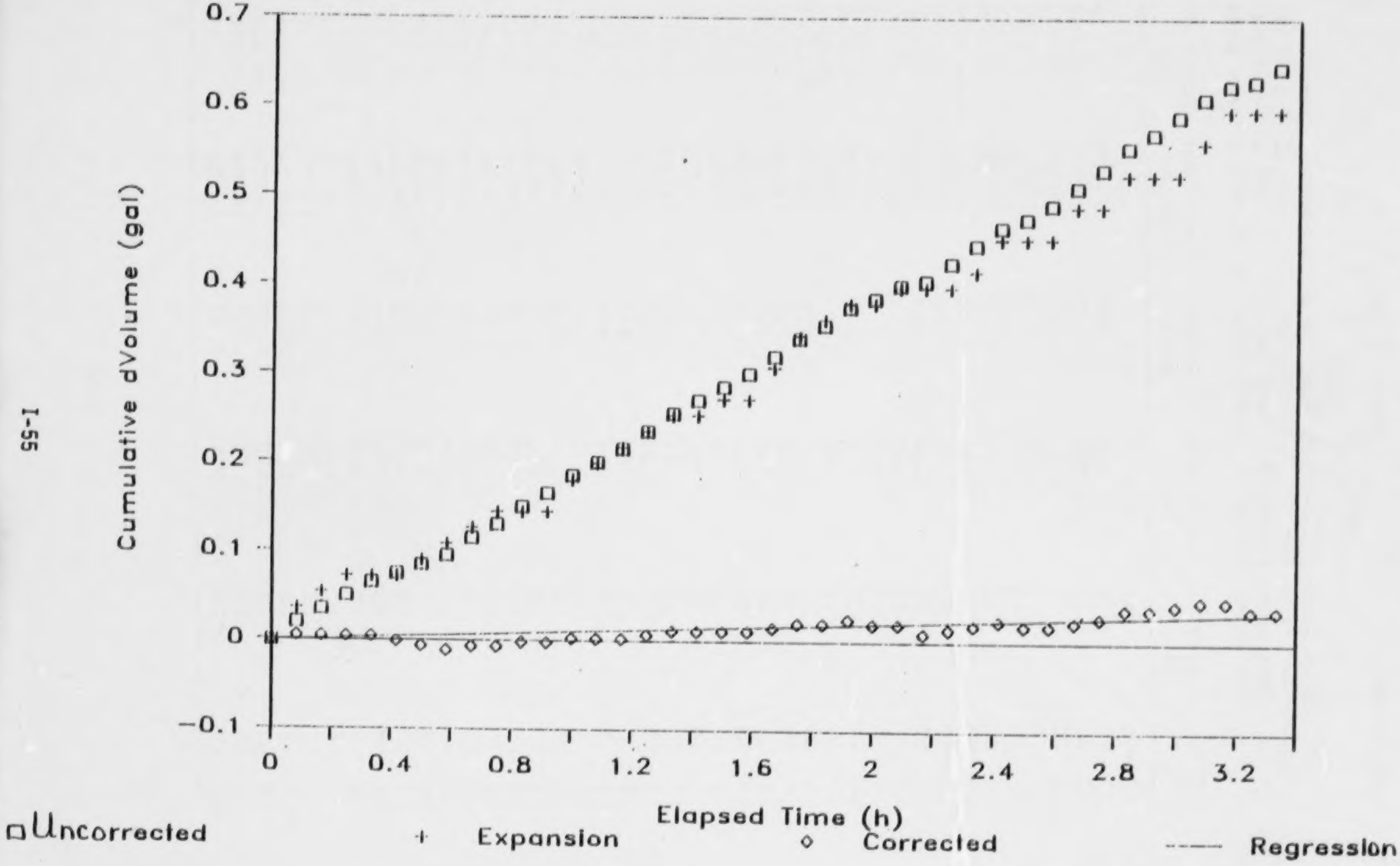
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
Cumulative dVolume (gal)
0
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2
Elapsed Time (h)
□ Uncorrected
+ Expansion
◇ Corrected
—— Regression